Education and research in Computer Aided Architectural Design in Europe

eCAADe 2013

Computation and Performance

18-20 September, 2013

Delft University of Technology

Volume 2

Edited by
Rudi Stouffs and Sevil Sariyildiz

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Theme

Computation and Performance

This is the second volume of the conference proceedings of the 31st eCAADe conference, held from 18-20 September 2013 at the Faculty of Architecture of Delft University of Technology in Delft, the Netherlands. Both volumes together contain 150 papers that were submitted and accepted to this conference.

The theme of the 31st eCAADe conference is the role of computation in the consideration of performance in planning and design.
Since long, a building no longer simply serves to shelter human activity from the natural environment. It must not just defy natural forces, carry its own weight, its occupants and their possessions, it should also functionally facilitate its occupants' activities, be aesthetically pleasing, be economical in building and maintenance costs, provide temperature, humidity, lighting and acoustical comfort, be sustainable with respect to material, energy and other resources, and so forth. Considering all these performance aspects in building design is far from straightforward and their integration into the design process further increases complexity, interdisciplinarity and the need for computational support.
One of the roles of computation in planning and design is the measurement and prediction of the performances of buildings and cities, where performance denotes the ability of buildings and cities to meet various technical and non-technical requirements (physical as well as psychological) placed upon them by owners, users and society at large.

This second volume contains 75 papers grouped under eleven subthemes that vary from *Simulation, Prediction and Evaluation* over *Models of Computation: Human Factors* to *Languages of Design*.

Rudi Stouffs and Sevil Sariyildiz

Sponsors of the eCAADe 2013 Conference

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Acknowledgements

With the 31st eCAADe conference held in Delft, eCAADe has finally come full circle. The very first eCAADe conference, before the actual founding of the eCAADe organization in 1983, was held in Delft in 1982. 31 years later, we are proud to welcome the eCAADe organization back to its origins.

This Delft conference has been a while in the making. The idea was first raised by Martijn Stellingwerff in 2006 and a preliminary proposal was presented to the eCAADe council at that time. However, we encountered some turbulent times with the destruction by a fire of the Faculty of Architecture building in Delft in 2008 and only in 2010 were we ready to present a definitive proposal for the conference in Delft. From that time until the publication of these proceedings, many people helped to make this happen and we hope to mention them all here:

First of all, we would like to thank both deans, Wytze Patijn (in 2010) and Karen Laglas (since 2011), for their endorsement and support, and especially the director of International Affairs at that time, Agnes Wijers, for her immediate support upon approaching her with the idea and for her ample support in the early planning of the conference event.

The eCAADe council was supportive throughout the entire process and helped with many aspects of the organisation. Both presidents, Wolfgang Dokonal (up to 2011) and José Duarte (since 2011), were very supportive. Bob Martens, as liaison with the conference host, was particularly helpful with many issues in the process. We received especially a lot of support from Henri Achten as previous conference organiser. Martin Winchester made sure the OpenConf system was running smoothly and reliably. Nele de Meyere and Maaike Waterschoot reacted promptly when approached with administrative questions. Financial support was generously provided by the sponsors Autodesk and Bentley Systems.

The Call for Extended Abstracts yielded 287 submissions. Fortunately, we were able to count on 135 international reviewers in helping us to assess all submissions (see the List of Reviewers section). Each submission was double-blind reviewed by three reviewers. Following the reviewers' recommendations, 150 papers were finally accepted for publication and presentation. We congratulate the authors for their accomplishment. Next to the authors, the reviewers, who volunteered valuable time and effort, the session chairs, who led the presentations, and the students and other volunteers, who assisted throughout the conference and its preparations, deserve our sincere thanks and acknowledgements.

As conference chairs, we had the support from the organising committee, including, Kas Oosterhuis, Joop Paul, Bige Tunçer, Martijn Stellingwerff, Michael Bittermann, Michela Turrin, Paul de Ruiter, Nimish Biloria and Henriette Bier. Joop Paul deserves a special note for securing Gerard Loozekoot, director of UN Studio, as keynote speaker. A special thanks goes to Irem Erbas, who, next to Bige Tunçer, Nimish Biloria and Michela Turrin, assisted in processing part of the proceedings. The secretarial team of the department of Architectural Engineering + Technology assisted on numerous occasions and Françoise van Puffelen, in particular, especially assisted in all financial matters. Thijs Welman secured the website and Martijn Stellingwerff designed the conference website. From the faculty we furthermore want to thank the FMVG (Facility Management and Real Estate) people who helped with the planning of and preparations for the event.

We are very grateful to have as keynote speakers at the conference Sean Hanna (as prominent

academic in the area of computation and performance), Shrikant Sharma (leader of SMART Solutions – Buro Happold's specialist service offering advanced computational solutions to practice) and Gerard Lozekoot (director and senior architect at leading Dutch architectural firm UN Studio) to provide their views on computation and performance to the conference.

We wish to provide a special acknowledegment to Yunn Chii Wong, head of the Department of Architecture at the School of Design and Environment, National University of Singapore, and Chris Magee, co-director of the SUTD-MIT International Design Centre, for offering their support to Rudi Stouffs to chair the preparations of this conference from abroad.

Finally, we want to thank Bige Tunçer, partner and colleague, and our families for their support and patience while we were spending late hours organising, reviewing, editing, and trouble shooting during the past three years.

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Rudi Stouffs and Sevil Sariyildiz

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Keynote Speakers

Sean Hanna

Sean Hanna is a Lecturer in Space and Adaptive Architectures at University College London, Director of the MSc/MRes programs in Adaptive Architecture and Computation at the Bartlett School of Graduate Studies, and Academic Director of UCL's Doctoral Training Center in Virtual Environments, Imaging and Visualisation. He is a member of the Space Group, noted as one of the UK's highest performing research groups in the field of architecture and the built environment.

Originally from a background of architectural practice, his application of design algorithms includes major projects with architects Foster + Partners and sculptor Antony Gormley. His research is primarily in developing computational methods for dealing with complexity in the built environment, including the modelling of space and its perception, and he is on the advisory boards of two related UCL spin-out companies. His publications address the fields of spatial modelling, machine intelligence, collaborative creativity, among others, and his work has been featured in the non-academic press, including the Architects' Journal and The Economist.

Shrikant Sharma

Shrikant Sharma leads SMART Solutions – Buro Happold's specialist service that offers advanced computational solutions to support architectural design, engineering, construction and operations of buildings and urban spaces. The team, founded by Shrikant in 2002, is renowned for delivering simple, innovative solutions for complex engineering problems in the built environment.

Shrikant has a PhD in Engineering and over 15 years of experience in the development and application of novel modelling and analysis techniques. A firm believer in the power of rapid design optioneering tools that integrate architectural, functional, engineering, and environmental assessments of buildings and urban spaces, Shrikant has been driving the development of a suite of intuitive real time software tools that work within commercial CAD and BIM environments. He has also led the application of such technologies for integrated modelling and optimisation on a number of projects such as Scunthorpe Sports Academy, Louvre Abu Dhabi, Sidra Trees Qatar Convention Centre, and London City Airport.

SMART Space - Buro Happold's crowd flow modelling and consultancy service is run by Shrikant. It uses novel analytical and simulation techniques to help the architects, planners, developers, and regulators to understand and optimise space layout, design and management.

Shrikant is actively engaged in the advancements in computation design and simulation through rigorous ongoing research and development, and has developed innovative software tools such as SMART Form and SMART Move.

Gerard Loozekoot

Gerard Loozekoot is Director and Senior Architect at UNStudio. He earned his Master's degree in Architecture from Delft University of Technology, worked as an architect at UNStudio since 2000 and became partner at UNStudio in 2008. His great interest are innovative typological innovations, such as the projects Theater in Lelystad, the UNStudio office tower in Amsterdam or the airport in Georgia. In addition, sustainable innovations are one of the main pillars of his projects. In Dienst Uitvoering Onderwijs in Groningen and Le Toison d'Or in Brussels, Gerard demonstrates that the added value of sustainable buildings have become the new standard. As director and senior architect is Gerard actively involved in all phases of the construction.

Contents

Simulation, Prediction and Evaluation

Using Smart Controlled AC and Ceiling Fan to Save Energy

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Abstract. *This research aimed to explore the energy savings through the use of smart control as well as ceiling fan in intelligent building. As the energy consumption of air-conditioning (AC) accounts for about 40% of total residential energy, therefore, applying smart control system to the use of AC to achieve the effects of comfy and energy savings should be able to generate positive effect for the energy consumption of overall residential. This study used the smart control system in the intelligent building lab to transmit message to AC for its implementation of next operating step through the indoor temperature sensor in order to achieve energy saving effect.*
Keywords. *Intelligent building; smart control; energy saving; ZigBee; smart living.*

INTRODUCTION

This study focused on the exploration of the smart controlled AC (Air Conditioner) and ceiling fan, using the lab of intelligent building, in order to achieve the objective of energy saving. Although each country has different definition about intelligent building, all of their basic objectives are about the same. Intelligent building combines structure, system, service and operation management to create the most optimal combination and process for the construction of highly efficient, excellent function and comfortable buildings. Therefore, intelligent building must be able to satisfy users' needs, control easily, save energy, improve management effectiveness and clarify information.

This study focused on the role of energy saving in intelligent building. Taiwan has started promoting the intelligent building mark since 2004; however, over the eight years, there were only ten cases certificated, which is obviously lower compared to 359 green mark buildings in the past. Moreover, although intelligent building has already became a government policy and Taiwan's Executive Yuan has also started promoting intelligent building since 2006, using buildings as medium to integrate ICT and other related communication products to merge innovation and design application for the construction of new living environment, there are still few of successful intelligent buildings over these years. The main reason is not because of the technology problem, but of intelligent building requiring the cooperation of many different fields under cross-platforms. Without proper guidance, architects are difficult to carry out plans and designs.

In view of this, our study tried to use established intelligent building lab to conduct smart control of energy saving on available AC and ceiling fan in the space so as to explore the future development and direction for intelligent building by means of energy saving efficiency.

METHOD AND DEVELOPMENT OF INTELLIGENT BUILDING'S ENERGY SAVING

An overview of building spaces utilization shows that, the proportion of electricity used by AC accounts for about 40% of overall energy consumption, while lights and electric outlets takes up about

Figure 1
Framework of smart home in lab.

40% (Taiwan Power, 2006). This study applied smart control to AC and ceiling fan as a main planning direction to compare its energy saving effectiveness to traditional model as a reference for future intelligent building design.

For smart controlled AC and home appliance, they can be automatically adjusted by different approaches. ,For example, conducting smart control on living environment through EEG (Electroencephalography) (Lin et. al., 2010); using BCI(Brain Computer Interface) as biological and electric monitoring system to achieve the goal of active environment control; applying CPSs (Cyber Physical Systems)such as Bluetooth, ZigBee RF and infrared ray to carry out various communication protocols so as to convert a variety of different signals through a smart control box (Bai, 2012) using pyroelectric infrared sensor-based indoor location aware system (PILAS) as receivers (Kastner et. al., 2010) to monitor residents' activities, position, pattern, or health condition to provide the best living environment; handling complicated intelligent home equipment by the construction of low cost sensor and control systems based on ZigBee (Blesa et. al., 2009); using low budget stationary sensor to set up electronic nose for air quality monitoring (Zampolli et. al., 2004) to control the AC system for the best air flow; providing different colors of light by photovoltaic lighting systems developed in accordance with human circadian rhythms which meet human body's different biological needs so that to enhance living safety and comfort (Fu et.al., 2010); setting up multiple ZigBee moisture sensor around the indoor space to adjust the AC operation, improve living condition and reduce energy consumption through temperature and moisture data collection (Wang et. al. , 2010); , using the position method of BBM (Best Beacon Match) to smartly control living environment (Jin et. al., 2007), such system can control AC and lighting; using Smart phone as interface to monitor and control the living condition (Zhong et. al., 2011) (Li et. al., 2012) to replace remote control; using wireless of sensor networks to establish a physical environment for room control to adjust the use of electrical appliances automatically for the energy-saving effect through the data monitoring (Yeh, 2009).

RESEARCH METHODS

This study used ZigBee as the main transmitter to construct an environment and interface which are able to meet the requirements of smart control (Figure 1), in which the temperature and moisture in the room were detected by sensor, and such data were then transferred to AC through ZigBee's signals which will further advise AC about the next step to take through the intelligent control way so as to achieve the objective of energy-saving

Most homes' AC temperature control uses re-

Figure 2
AC controlle key functions.

turned air flow temperature as a basis to judge the next operating step of AC. Ceiling fan is a good way to condition the indoor air flow, and the room temperature can be rapidly and effectively reduced through the combination of these two appliances. However, f to adjust its frequency reduction or air conditioning running adjustment, the AC requires the room temperature reaches the pre-set value prior to starting its next operation. As the purpose of AC is not for cooling the entire room but for users only, therefore, this study used portable sensors near the users which can send back detected temperature data around the users back to AC every thirty seconds for AC's next operating preparation (such as reducing frequency, changing to air flow or reducing wind flow) without waiting for the reach of pre-set room temperature.

As the moisture sensor is portable and can respond the temperature near the users to AC immediately, it is with real time feedback feature and energy saving effect compared to the perception mode of traditional AC.

Most Home ACs are divided into fixed- and variable-frequency of window and wall mounted models. This study used fixed-frequency, wall mounted AC which has been used for five years and can be controlled through the remote control in terms of power switch, temperature, function, timer, fan speed, rhythm, sleeper, particularly the Fuzzy modes which uses the body perception condition as feedback data for AC's operating reference.

Although our lab controller only has 12 keys, the study's smart control model can simulate 32 controller functions, through different setups ways. For example, despite that there were only two temperature control keys (up and down), the temperature can be set from 17 °C to 31 °C; function key can control four modes of ATC, AC, dehumidification and fan; Fuzzy key has options of too hot, comfy, and too cold; fan key can set speed at high, mid, low, and auto; timing key can set time from 0.5 to12 hours; while most keys only have one function, all of them have on and off options. In sum, there are 48 different options in total (Figure 2) which are more than the 32 control functions set by this study. Owing to each brand's AC controller is different, how to choose the best control option in order to achieve energy saving and comfort will be the central topic of this research.

This research focused on room comfort as the main objective and, coupling with the energy saving objective, explored how to set up the best operation mode among the 32 simulated functions for energy saving and room comfort.

Most home AC (such as variable-frequency AC) will start to lower the compressor turn rate to save energy and maintain room temperature when the self-perception function detects the temperature of return air reaching the set temperature, and start to run the compressor again to low the temperature down once the room temperature raised to a certain degree. This study used fixed-frequency AC with compressor can only be operated with on or of function but cannot be operated as efficient and energy-saving as variable AC compressor in terms of maintain the indoor temperature through the change of frequency.

In this study, when the indoor temperature in the intelligent building reaches a preset limit, the controller will place to AC an order to implement next operation. Instead of by AC itself, it used the external sensor to detect the current room temperature and then issue the next operating order. Owing to that the study could only use the function key on remote controller key as simulation object

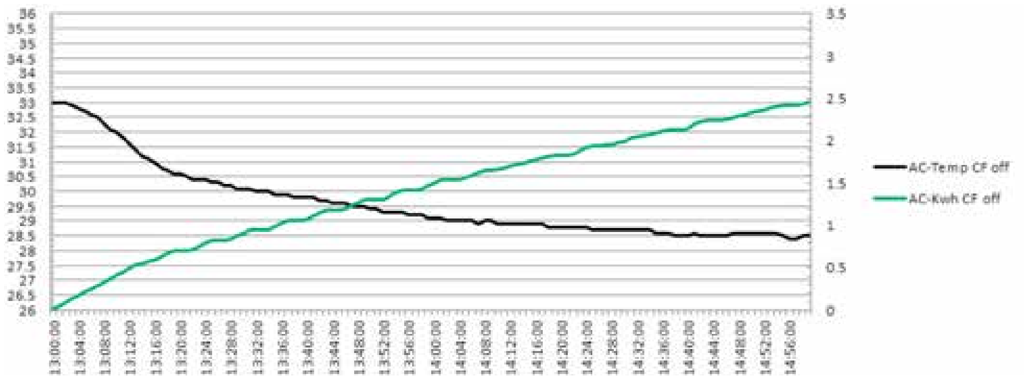


Figure 3
The measured indoor temperatures and energy consumptions of AC mode under the condition of 26 °C of temperature as well as the shutdown of ceiling fan on May 16.

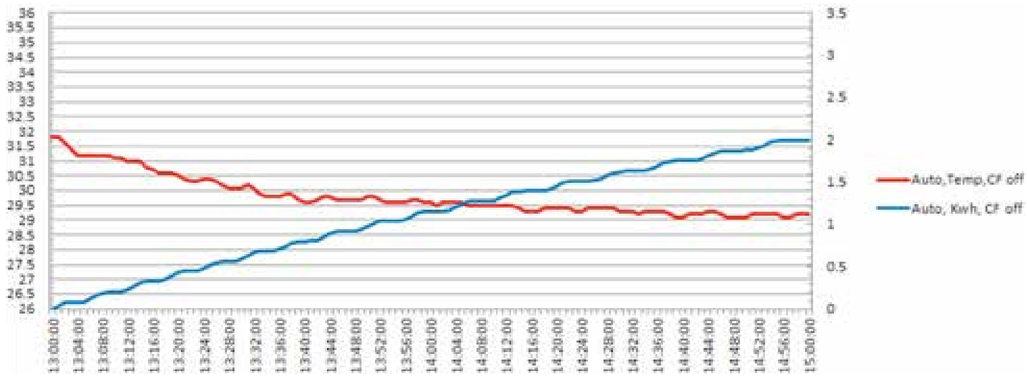


Figure 4
The measured indoor temperatures and energy consumptions of AC automatic mode under the condition the shutdown of ceiling fan on May 17.

to select the most suitable mode for the next step order placing, therefore, this research attempted to explore how to use the current transmitter to let the AC knows that the temperature has been reached as well as what's next step it should operate in order to achieved the objectives of energy saving and comfy.

EXPERIMENTAL PROCEDURE AND RESULTS

As the AC used in this lab. was a fixed-frequency split air-conditioning being used for five years, in order to confirm whether the use of intelligent control of energy efficiency is achieved as expected, this study first carried out the multi-day tests and records for the AC mode controlled by remote controller and automatic mode. Owing to the unstable temperatures of spring season during the experimental period which gradually became warming, in order to obtain a more objective analysis of the data, this study set the value at room temperature of 26 °C and implemented four days' records and observed the temperatures and energy saving effects on the above-mentioned two air conditioning modes, then explored the indoor ceiling fan impact on AC effect on the basis of data test. The gateway controller used in our laboratory was able to record indoor temperature and total electricity consumption every minute. The findings showed that, under the condition of indoor fan shut down as well at the temperature of 26 °C, the room temperature was only reduced to 28.5 °C and 29.2 °C, respectively (Figures 3 and 4). Moreover, despite the air conditioner au-

Figure 5
The measured indoor temperatures and energy consumptions of AC mode combining with ceiling fan on May 14.

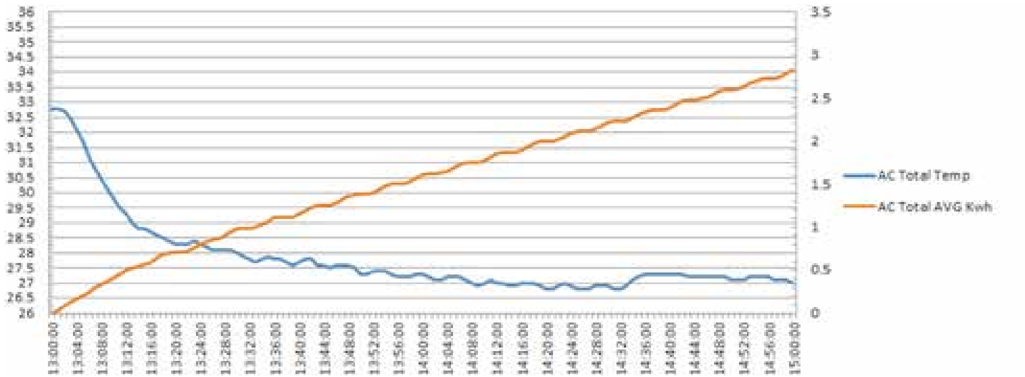
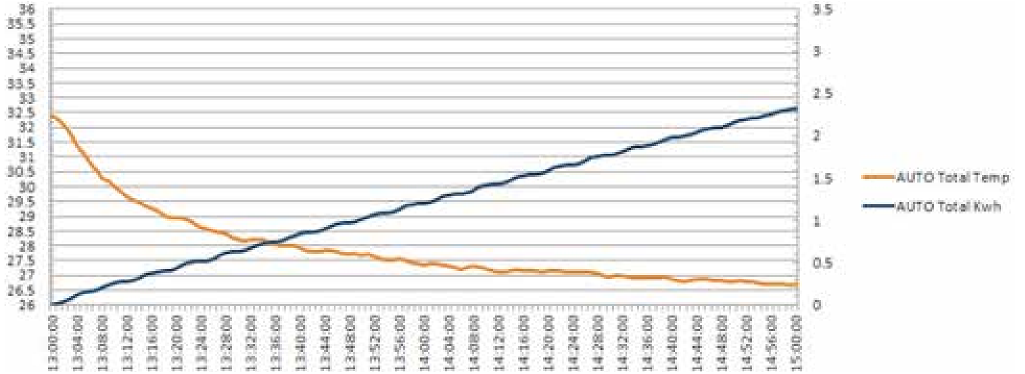


Figure 6
The measured indoor temperatures and energy consumptions of AC automatic mode combining with ceiling fan on May 14.



tomatic mode reached the energy consumption of 1.995kw in 2 hours, the quality of the indoor temperature cannot achieve the desired comfort.

After opening the indoor ceiling fans to help improve indoor air circulation under the same AC and automatic AC mode at temperature of 26 °C, the room temperature value showed a significant improvement trend (Figures 5, 6).

Test results of these few days revealed that the split air conditioner in our study neither could reach desired temperature within two hours nor reduce the indoor temperature to a reasonable value, despite that indoor temperature showed a dropping trend. This phenomenon showed that the air temperature sensor was located in a place which was not able to detect the room temperature value correctly, resulting in the AC failed to carry out proper cooling effect in accordance with the actual indoor temperature value.

While coupling with the ceiling fan under the same set, value of the room temperature improved significantly and the indoor temperature was fairly satisfied -though not reaching but was closing to the set temperature of 26 °C.

Based on the AC automatic mode and its achievable target temperature values, this study set different smart modes for the controller to test and record the AC's energy consumption situation.

- The temperature was set at 26 °C and the gateway controller would transmit message to AC to change the mode to fan mode when the room temperature reached 26 °C, or restarted

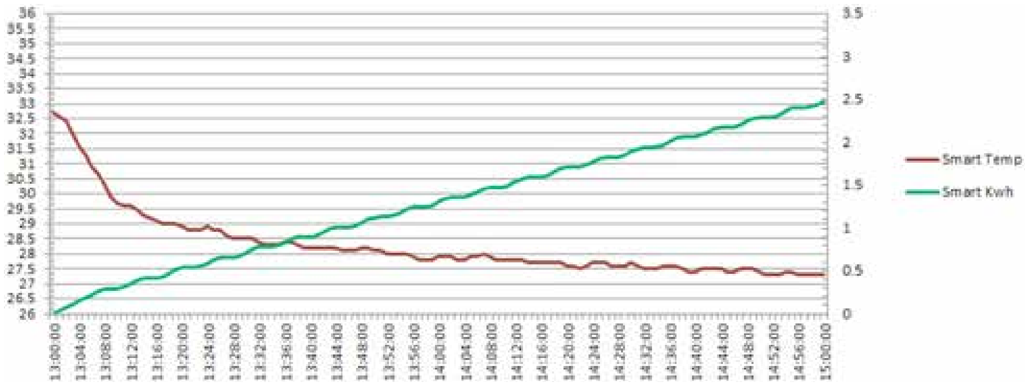


Figure 7
The measured indoor temperatures and energy consumptions of smart control mode on April 25.

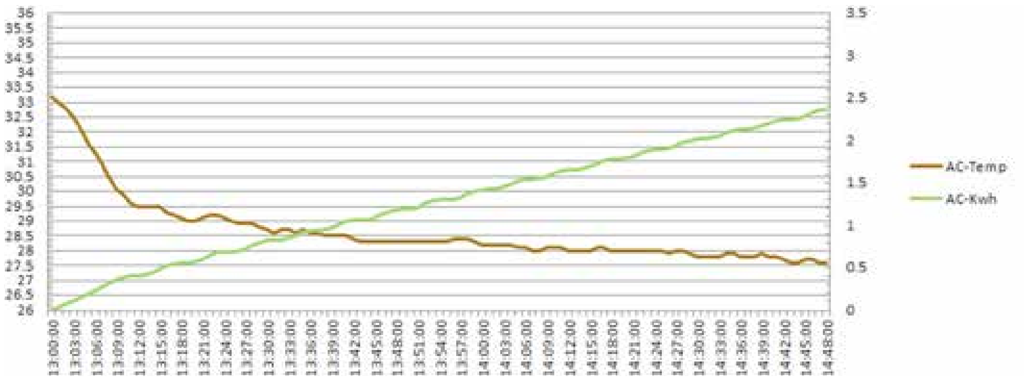


Figure 8
Demanding the AC to cool down rapidly by setting temperature at 24 °C and ordering AC to change to fan mode when the temperature reached the set temperature, and to restart the AC compressor when temperature restored to 27 °C.

the AC compressor when the indoor temperature rose to 27 °C, so the cycle execution. The initial findings showed that, although the temperature was set at 26 °C, the indoor temperature was unable to cool down to 26 °C. Two possibilities are judged for such condition: A. Sensor mounted on the AC was too close to the outlet which led too high return cool air rate, thus causing the inconsistency between the temperature detected by the sensor and actual indoor temperature and resulting in automatic control mode failed to perform its function. B. The variation of detected temperature between sensor of this study and sensor mounted on the AC. After examination, it was found that there was 1°C difference between both sensors which led both operating modes of two hours test to exert the same effectiveness (Figure 7).

- The temperature of AC was set at 24 °C. When room temperature reached 24 °C, the AC would be ordered to change into fan mode, and would restart when indoor temperature rose to 27 °C. The results of measured data showed that, indoor temperature dropped from original 33.5 °C to 29.5 °C within ten minutes, but then gradually cooled to 27.5 °C in the rest 110 minutes (Figure 8), failing to reach the expected set temperature. The observations made here for such condition were that, in order to avoid excess use of AC, both ACs used by classrooms and lab. were adjusted and set. Therefore, no matter how the air temperatures were adjusted, the compressor would maintain a certain operation mode which was difficult to change.

Experimental data showed that, as the intelligent control mode could only be operated by cool and fan modes which limited its compressor operation in terms of cooling and electricity consumption adjustment, its electricity consumption was almost the same as that of automatic AC. On the other hand, due to the operation mode of AC used by the school was adjusted before installation for the purpose of energy saving, it was incapable to reach expected temperature through the temperature adjustment.

Furthermore, the data also indicated that, without the ceiling fan to adjust air flow, indoor temperature was not only difficult to low down, but with significant fluctuation as well. Therefore, it is obvious that ceiling fan does help the indoor temperature to cool down.

CONCLUSION

The lab was constructed in winter time December, 2012, but did not start carrying out the experiment until the mid-April of next year when the weather was getting warmer. During the experimental period, this study discovered that when the initial indoor temperature became higher, the electricity consumption was also affected. However, the preliminary findings showed that the current operating mode of fixed-frequency AC was difficult to achieve the objective of energy saving through control method of smart system. Therefore, it is recommended that the future study should focus the application of smart control on AC with variable frequency in order to find out possible smart control mode to meet the demand for energy saving.

Owing to the shorter experimental period, the accumulated data of initial room temperature values in this study were rather limited and cannot be regarded as objective data to present the relationship of electricity consumption effectiveness between the indoor temperature and AC operation. This research will continue to apply different AC operating modes as well as statistical analysis to explore the relationship between the temperature of AC operation and electricity consumption, in order to identify the most energy-efficient mode of operation as a reference for future smart control studies.

The AC currently used by school have been adjusted which are not suitable for the test of energy consumption through temperature control of smart mode. However, as now the school has approved to have the lab AC restored to their original setting condition, the related experimental modes of this study will be continuously conducted in order to obtain more objective experimental data for the references of indoor temperature quality control and adjustment.

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Even 'Clouds' Can Burn

Fire engineering simulation for a safe, innovative and high-performance architectural design - a case study

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Abstract. *Architecture, nowadays, is an even more demanding activity in which complexity is the keyword: complex forms, complex functions and complex structures require sophisticated facilities and components, for example, 'The Cloud' of D. and M. Fuksas in Rome. These complexities can give rise to numerous risks, among which fire is frequently a central problem.*
The fire safety norms do not involve an approach integrated with other instruments or building model (BIM), but provide a list of information and constraints. These codes are now shifting away from a prescriptive-based towards a performance-based method due to recent progress in fire safety engineering.
Following this approach, a case study simulation of a multi-purpose centre was carried out in Tivoli, near Rome. This simulation allowed greater freedom in architectural composition, a lower risk to people, a larger number of material and building components used and higher safety standards to be achieved. The model is based on the FDS (Fire Dynamics Simulator) language, a simulation code for low-speed flows, focused on smoke, particle and heat transport by fire.
Keywords. *Architectural design; computational fluid-dynamics; fire propagation; fire safety; smoke propagation.*

FIRE AND ARCHITECTURAL DESIGN

Architecture has always been a demanding activity, but in present times, has had to face intertwined problems in which complexity is the keyword: complex forms, complex functions and complex structures require sophisticated facilities and components. These complexities can give rise to numerous risks, among which fire is frequently a central problem (Harper, 2004).

Existing fire safety regulations and codes (Balaban et al., 2012) very often actually represent as many limitations imposed on architectural needs such as space layout, free form space, distribution path, space occupancy and aesthetic quality. Fire safety, more specifically smoke and heat extraction, requires optimization and careful analysis in the early design phases. These norms are the average of real fire safety cases, and so in some specific cases, they are more demanding than strictly necessary with regard to devices or shape layout, while in others they could actually be insufficient.

An impressive example of the impact of fire regulations on architecture is represented by the recent design competition for the new Rome Conference Centre in 1998. It is situated near the old one, in the district of the *Esposizione Universale Roma* - *EUR* (Rome Universal Exhibition) planned for 1942 where, according to Mussolini's town plan, important ministries would subsequently be transferred. The old Conference Centre was designed by Adalberto Libera in 1939 and is a reflection of late Italian rationalist style tinted with a superficial, ironical and monumental classicism. There were numerous important responses to the 1998 competition call and several high quality projects were selected. Many were based on mimicking the symmetrical and constrained layout resulting from a simplistic interpretation of the apparently elementary nature of the EUR buildings. Another important motivation was the difficulty to take into account current safety rules regarding structure, plant engineering and evacuation paths in a free form space configuration.

In many cases, this design logic led to the various conference halls being situated as low as possible and for fire fighting purposes to use water cisterns (filled with water) at the top of the building. These design solutions had the following consequences: overloading at the building top, which is a design solution to be avoided in view of the seismic nature of Italian territory; an obstruction of the visual permeability between inside and outside in order to respect the fire resistance of the walls; the denial of whole roof level availability and limited panoramic view due to the presence of cisterns. Other examples are: the Twin Towers, which had cisterns on the roof that unfortunately failed to cope with the combined effect of fire and the abrasion of the intumescent paint protecting the steel structure; or the first HKSBC projects in which water inside the pillars was thought to cool the structure at the price of adding permanent loads.

The engineering approach makes it possible to exceed the limits prescribed by the codes and at the same time rigorously respect safety as the norms regulate only average scenarios. This approach allows designers to have a greater compositional freedom, obtaining innovative and high-performance buildings in which fire safety has become an essential element of architectural conformation. In other words, fire engineering is used to allow fire safety to be demonstrated, despite its peculiar form and dimension like the new Congress Palace in Rome designed by D. and M. Fuksas - familiarly called "The Cloud" [1, 2]. In this case, it was possible to use fire engineering simulation techniques to demonstrate that the danger, in the case of fire, was very low as the space enclosed by the 'glass box' could be considered an open space and as the thinness of the membrane enveloping 'The Cloud' renders the fire load negligible.

This approach has allowed modifications to be avoided during the detailed building design phase that might compromise the identity of the project.

FIRE SAFETY PRESCRIPTIVE APPROACH

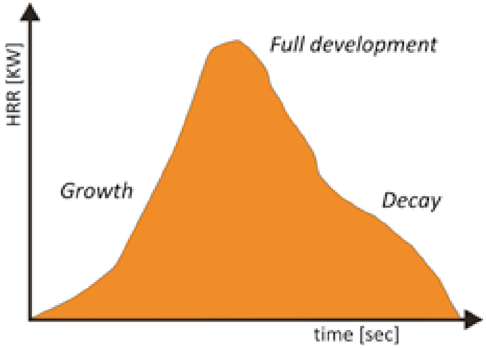
The combustion process is a sequence of chemical reactions between a fuel and an oxidant, accompanied by the production of heat, smoke and the conversion of chemical materials. The process can be specified by means of the Fire Triangle, which is composed of fuel, oxygen and a heat source. It is essential for a correct relationship among these three elements otherwise, combustion itself cannot take place (Harper, 2004).

Inside a *compartment* - i.e. a homogeneous and limited part of the building with respect to function, use destination and fire safety class - it is possible to identify four fire phases (La Malfa, 2009):

Ignition, a heat source acts on the fuel, and if sufficient thermal capacity is released, it warms it up to its ignition point. The thermal energy needed to attain the ignition temperature depends on size and the ratio between the mass and the surface exposed to the air.

- *Growth*, the fuel materials are heated and tend

Figure 1
The HRR curve over time during burning process.



to reach their ignition temperature. The spread of the fire produces: a reduction in visibility, increased toxic fumes, increment of the burning rate over time.

- *Development*, all combustible materials in the *compartment* are simultaneously involved in the burning process due to the irradiation caused by the products of combustion: the "flashover" phenomenon.
- *Decay*, the fire tends to slow down owing to the progressive reduction of combustible materials or oxygen and starts to be extinguished.

Codes do not involve an integrated approach nor do advanced CAD tools like building information modelling - BIM, but they do provide a list of documentations and prescriptions to be fulfilled, which are useful in the early design phases (Balaban et al., 2012):

- *Definition of project*, detailed description of building with particular reference to ventilation openings, fire and smoke *compartments*, structure and distribution of furniture and combustible materials;
- *Fire safety objectives* and indication of *performance requirements*, in relation to specific architectural goals and to requirements for which the analysis is applied (maximum gas temperature at human head height, visibility, air concentration of toxic substances);
- *Determination of fire scenarios*, schematizing events that may occur in relation to the characteristics of fire, the building and the occupants;
- *Method of contrast*, for the achievement of the safety objectives set (obstacles to combustion product propagation, smoke devices, fire extinguishing systems and fume extractors);

FIRE SAFETY PERFORMANCE APPROACH

Building codes are shifting from a *prescriptive-based* method towards a *performance-based* method due to the progress in fire safety technologies, including the development of an engineering approach (McGrattan et al., 2010; Hadjisophocleous and Benichou, 1999). The traditional *prescriptive* method uses a set of technical standards that are rigidly applied in a 'mechanical' way. The *performance* method allows the actual risks for specific activities to be evaluated step-by-step by means of careful analysis and simulation.

In Italy, the engineering approach to fire safety is regulated by laws, the most important of which (D.M., 2007) defines the procedural aspects and criteria for assessing the level of risk and consequently the mandatory design measures intended to contrast possible code violations.

Heat Release Rate Parameter

The *Heat Release Rate* - HRR - is the main parameter governing the fire phenomenon; it influences many other fire characteristics. Literally, the HRR indicates the heat released by the combustion of a material over time per unit surface area (Babrauskas, 1991).

The area under the curve (Figure 1) represents the energy released during all *phases*, while, for the purpose of fire safety, it is essential to evaluate the phase preceding the *flashover*s, because after this time conditions are created that are unsustainable for the human body.

For this reason, it is necessary to know the variation over time of the actual *fuel mass involved* which, in the *growth phase* of the fire, is expressed by the equation (1). It displays different curves pertaining to fire growth (Figure 2) depending on the time "t" by means of a quadratic function and on the constant "α" that takes into account different material types. The combustion speed can be: *slow*, α = 2.77

$\times 10^{-3}$ KJ/s^3; *medium*, $\alpha = 11.11 \times 10^{-3}$ KJ/s^3; *fast*, $\alpha = 44.44 \times 10^{-3}$ KJ/s^3; *ultra-fast*, $\alpha = 177.77 \times 10^{-3}$ KJ/s^3 (La Malfa, 2009).

$$HRR = \alpha \times t^2 \qquad (1)$$

The curves do not grow indefinitely, but reach a peak and then begin to decrease, so the quadratic part refers only to the crescent monotonic curve. The decay phase, for common materials, accounts for 20÷30 % of the whole combustion process.

Curve peak values change according to the material being burnt. For example, plastic rubbish has a peak of 80 KW, while a car can reach 6000 KW.

As the HRR increases, also the temperature and the rate of temperature rise increase, thus accelerating fire development. In addition, increased HRR results in reduced oxygen concentration and increased production of gaseous and particulate matter; these are fundamental factors to be considered for fire safety.

Material Reaction Rate to Fire

For a given material, the reaction can produce a solid, denoted as *residue*, plus water vapour and/or fuel gas; for instance, the evaporation of water from a solid material is described by the reaction that converts liquid water-to-water vapour (McGrattan et al., 2010).

A pyrolyzing solid in a reaction produces a solid *residue*, *water vapour* and *fuel gas*, the sum of which has the same weight; this means that the mass of the reactant is conserved.

Another important parameter to consider is the *mass fraction* that can be burnt at time "t" (Figure 3, blue curve) of the normalized density of material, which decreases as the sample is slowly heated. The *reaction rate* (Figure 3, green curve) is the rate of change of the mass fraction at time "t"; where this curve peak is referred to as the *reference Temperature* "T_s", which is not the same as the ignition temperature, but is the most important parameter for defining the *reaction rate* of a material.

Equation (2) defines the *reaction rate* - "r" - at *reference Temperature* T_s [°C], of the -ith material undergoing its -jth reaction; $Y_{s,i}$ defines the ratio between

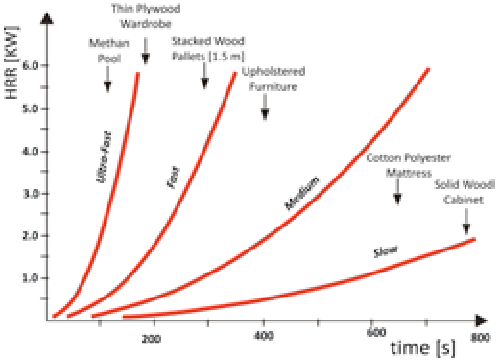


Figure 2
The HRR curves over time for different materials.

the density of the -ith material component of the layer at temperature T_s, divided by the initial density of the layer.

$$r_{ij} = A_{ij} \times Y_{s,i} \times \exp\left(-\frac{E_{ij}}{RT_s}\right) \qquad (2)$$

The model used is based on the FDS (Fire Dynamics Simulator) language, a simulation code for low-speed flows, focused on smoke, particle and heat transport by fire. This model provides the estimation of the fire's evolution, dividing the space into a large number of small contiguous elements where the thermodynamic state is calculated by solving the conservation equations of mass, energy, etc. (Ozel, 1998). methods and analysis of results, the field

This approach allows the problem to be solved by integrating a set of partial differential equations for the whole system, thus avoiding the explicit treatment of the boundary conditions. One of the

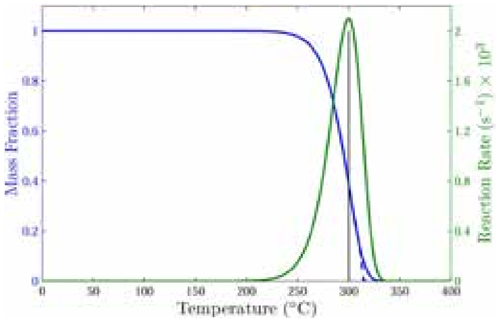


Figure 3
Reference Temperature. T_p= 300 °C ; r_p= 0.002 s^(-1); T= 5K/min ; v_s= 0.

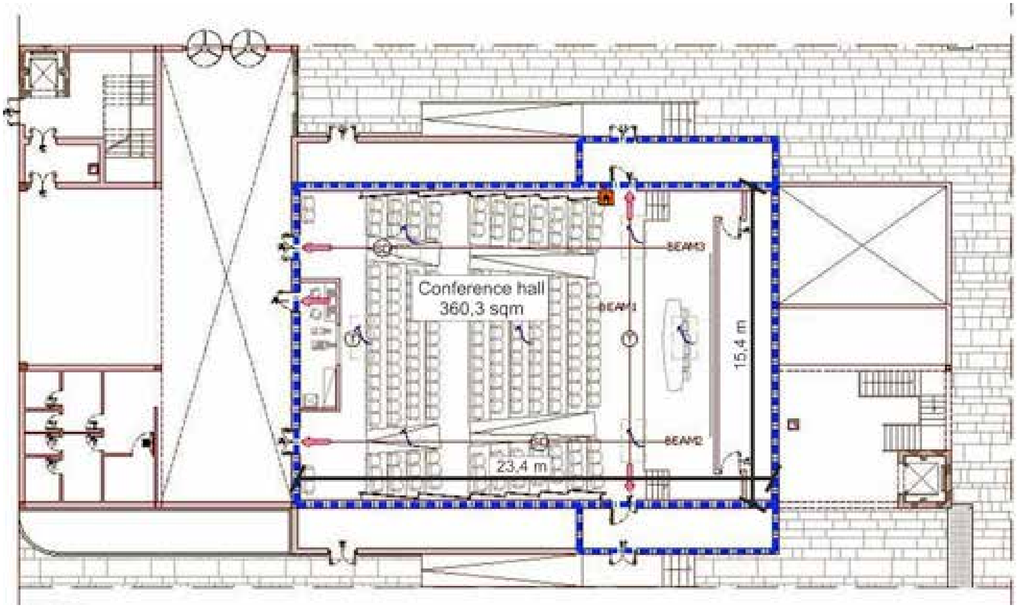


Figure 4
Case study of a multi-purpose exhibition centre at Tivoli - the conference hall. The dashed blue lines define the compartment and the BEAM devices measure the total obscuration rate between two points.

main calculation problems is the actual choice of mesh: decreasing the size of the elements, a more realistic simulation is obtained, although this requires a longer computation time and greater hardware power.

The mathematical model used for solving the analysis of fire phenomenon and interface problems among contiguous space elements is the *phase field* model (Boettinger et al., 2002) that, by means of a specific and infinitesimal mesh, can correct dynamic interface problems.

MULTI-PURPOSE EXHIBITION CENTRE AT TIVOLI - CASE STUDY

The case study was an experimental master's degree thesis of a project for a multi-purpose exhibition centre with a multi-storey underground parking station in Tivoli, near Rome; the simulation was focused on the *compartment* of the conference hall (Figure 4).

The fundamental value to be specified was, as previously mentioned, the *Heat Release Rate* - HRR. This was schematized with a *burner*, on which a *vent* was applied, which simulated a fire that released heat but also a specific quantity of *particles* and *gas*, based on input data. The levels of HRR developed from the case study are based on information derived from the experimental data and compared with the values identified in the technical literature for those specific activities.

In the case of a multi-purpose hall, the presence of scene panels is assumed (Table 1) which increases the total fire load.

A rapid decrease of the HRR was observed due to the action of the simulated sprinkler system (automatic opening), giving a value of the fire extinction coefficient. This was made possible only through the correct sizing of the sprinkler piping, by indicating the flow of the single sprinkler obtained from the product specifications and the UNI regulations (UNI EN 12845, 2005).

Some fire scenarios of NFPA 101 (Coté and Harrington, 2012) were determined in compliance with the law (D.M., 2007). Relevant critical scenarios representative of the actual conditions were produced

Furniture type	[MJ/One]	Quantity	Sur.Compartment [m²]
filing cabinet (included content)	2009	1	359
big lamps	160	30	359
small lamps	50	50	359
armchairs	335	206	359
secondary electrical panel	300	1	359
metal desk	837	1	359
chairs	67	2	359
big table	590	1	359
Product type	**[MJ/m²]**	**Quantity [m²]**	**Sur.Compartment [m²]**
electrical equipment	670	1	359
telephone and PC	200	1	359
electric cables	600	1	359
ceiling	1200	9	359
metal rods	800	2	359
sound-absorbing panels	6000	9	359
wood flooring	1200	9,2	359
wood doors	1800	0,6	359
spotlights/optical instruments	200	1	359
coating wall	1500	9	359
scenographic panels	3500	30	359
projection screen	1000	4	359

Table 1
Fire Load calculation in relation to the furniture or product type.

using: a preliminary check of regulations; expected performance levels; considering, for additional safety, the failure of the sprinkler system or devices for automatic door opening. It was also possible to simulate fire scenarios that are worse than the NFPA 101 code fire scenarios. Those could be the most severe fires ever recorded, or the average of the worst fires having occurred with some regularity. The fire scenarios were examined for a period of 10 minutes, an appropriate time for a preliminary investigation (Figure 5 and 6).

The choice of particulate *reaction rate* is one of the most critical aspects (Kittle, 1993): for example, in the pre-flashover phase, a modest amount of electrical equipment could spread smoke more dangerously than a common fire with greater reaction rate levels.

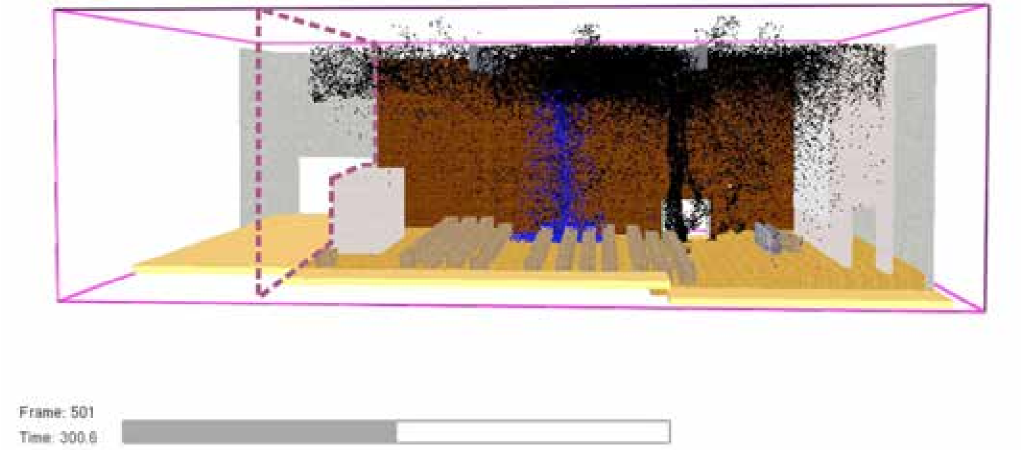
All the simulations verified the fire scenarios considered by analysing variations of: gas temperature at human head height and at construction element height (by temperature detectors - THCP); curve of heat release HRRPUA [KW/m²] derived from the sum of the value of the initial burner plus any contribution of fuel elements; visibility in the room for the egress time (by rate dimming detectors - BEAM); fume, particle and heat flow trends in the *compartment*; sprinkler operation.

The main architectural problems were encountered both:

- outside the building, the relationship with the square (quality of urban space)
- inside the building, the layout of the conference hall within the overall shape of the building (quality of architectural composition).

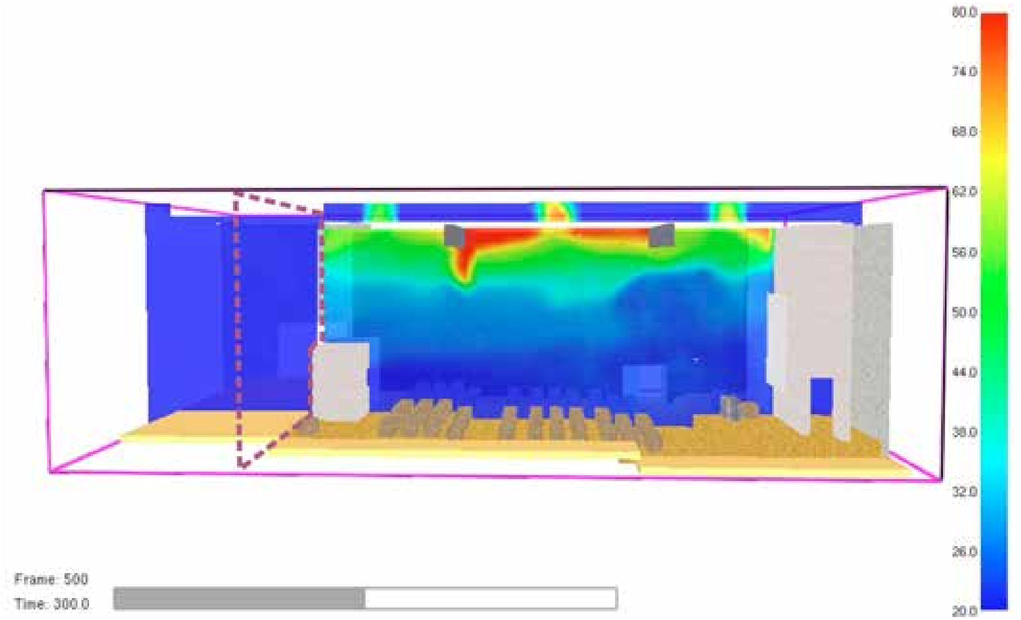
As far as the first point is concerned, namely the urban environment, two aspects must be taken into consideration which heavily affect the architectural composition and the cost of the building: the time required for firemen to arrive from the nearest fire station and the building conformation, which is linked to the constraints imposed by the underground parking safety openings. In the case of the

Figure 5
Particle diffusion showed in a longitudinal section of the multi-purpose conference hall study case 5 minutes after fire ignition.



first aspect, the most important features are the non-combustible nature of the materials used and/ or the time needed for the bearing structure to resist until the fire fighters arrive. This aspect seems to be mainly dependent on the materials used and to exclude any reference to the 'form'. In actual fact the shape of the building, of its interior and the accesses to it constrain the possible manoeuvres of

Figure 6
Gas temperature showed in a longitudinal section of the multi-purpose conference hall study case 5 minutes after fire ignition.



the fire fighting and rescue vehicles and the extinguishing of the fire. The second aspect, the shape of the building and of the surrounding area is directly affected by the large air wells required to make the underground parking levels comfortable and safe. It was observed that by simply applying the codes literally, these 'wells' heavily affected the restaurant area, unless the latter was shifted further north and thus could not be used in the winter. However, applying the model to an alternative proposal for the location of the 'wells' in such a way as to leave the positioning of the restaurant unchanged and simulating the fire process, it was possible to verify the safety.

As far as the second point is concerned, as for example the compartment of the multi-purpose hall, according to the code (UNI 9494-1, 2012), the smoke and heat exhaust openings must have a continuous surface as long as the corridor length at a height of over 1.2 meters, thus conditioning the compositional, formal and acoustical aspects. In addition, the façade would have to be constituted by solid and non-combusting materials with high temperature proofing. The simulation verified safety standards also with a less invasive action on architectural composition, thus allowing different materials and shape. The simulation computed that the required fresh air brought into the conference hall only through emergency doors was enough for people, for structural safety and for visibility even if the opening (doors and windows) size of the walls did not satisfy those codes. After an accurate simulation, glass façades were allowed as they would be shattered by the high temperature at the beginning of the fire process. This is dependent on the capacity of fire engineering simulation accurately to predict the fire status.

CONCLUSIONS AND FUTURE PROSPECTS

The simulation performed led to better use of the urban square (the prescriptive method imposed huge underground parking ventilation openings); more freedom in architectural composition (codes constrained doors and windows position and size); reduced risk to people; freedom in the use and choice of a larger number of materials, furniture and building components.

Moreover, if the traffic regulations governing the area outside the building were to change and cause a delay in the arrival of the fire fighting vehicles it would be possible to simulate the behaviour of the fire in the building to check whether in any case the safety of visitors and staff were guaranteed or whether any further action was necessary and the extent thereof. This simulation, extended to all the buildings affected by the change in traffic regulation, would entail at the town planning level a detailed estimate of the costs/benefits-safety ratio.

The main difficulty encountered in the use of the simulation model was due to the limited interface with other CAD programs as it exports only 3D (AutoCAD®, Blender®). The integration of this analytical model with BIM would be desirable, as has already been done with structural and thermal calculation programs. An integrated design could thus be totally exploited in the building process, thus facilitating collaboration and information exchange.

This study, which was developed in the form of an experimental master's degree thesis, should be included in an academic course. In Italy, although there are many post-graduate professional courses concerning the applications of fire safety, most academic students ignore fire safety problems, so they should be taught at least the main principles for fire safety and, secondly, those for high-performance buildings.

Nowadays, the buildings are often readapted through a change of use, resulting in fire load variation; besides the building codes are constantly changing, giving rise to maintenance and accommodation activities with additional costs not specified in the design process. Moreover, the relationship between the study of fire phenomena and architectural conformation becomes fundamental in historical buildings, where architectural restrictions and heritage preservation do not actually go hand in hand with fire safety needs. All these problems can be faced by means of the fire engineering simulation approach that allows performance evaluation during a building's lifetime.

Fire safety engineering should not be interpreted, in the narrow sense, as a tool allowing the prescribed regulations to be sidestepped, but as a system model that can analyse real cases in depth, afford more solutions to problems, achieve higher safety standards and a more accurate evaluation and analysis of the risk of fire, so as to reduce problems from the outset. For example, in Italy this approach, when adopted, has led to a new image of steel structures completely free of protective coatings (intumescent paintings or cement or stucco or aluminum and insulation panels), with evident savings in construction costs.

The performance-based method allows a preliminary evaluation during the design process, avoiding not only increased costs but also modifications that often distort the identity of the building.

The use of these tools during the various phases of new construction design or in rehabilitation projects regarding existing buildings or during a building's lifetime can allow designers and the competent authorities to collaboratively develop projects, ensuring enhanced security also at urban level. There are two possible future developments of these tools: a numerical one, through integration with other multi-physical tools (e.g. COMSOL®), or a semantic one using ontology tools and AI methodologies.

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Inductive Aerodynamics

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Abstract. *A novel approach is presented to predict wind pressure on tall buildings for early-stage generative design exploration and optimisation. The method provides instantaneous surface pressure data, reducing performance feedback time whilst maintaining accuracy. This is achieved through the use of a machine learning algorithm trained on procedurally generated towers and steady-state CFD simulation to evaluate the training set of models. Local shape features are then calculated for every vertex in each model, and a regression function is generated as a mapping between this shape description and wind pressure. We present a background literature review, general approach, and results for a number of cases of increasing complexity.*
Keywords. *Machine learning; CFD; tall buildings; wind loads; procedural modelling.*

INTRODUCTION

It is generally recognised that architects currently require performance information to guide their decisions almost from the inception of a project. In fact, there is a mentality present of simply trying to collect as much data as possible with the intention of synthesising it into a situated design response. This presents a problem, especially for computational fluid dynamic (CFD) wind simulation, whereby the time required to assess the performance is obstructive to the fast and iterative nature of current parametric design softwares. This is possibly due to the tendency for architectural software tools to originate in engineering fields, without due consideration of speed-accuracy tradeoffs to adjust for the application requirements (Chittka et al., 2009; Lu et al., 1991). In other words, they are typically too accurate and slow for the fast pace of modern conceptual design, massing or form decisions. Developing a method that can give real-time performance feedback about a form allows for intuitive play of the kind we are used to with physical models.

Wind engineering has traditionally been within the remit of engineers or specialists, with numerical simulation (CFD) considered a supportive tool to physical boundary layer wind tunnel (BLWT) testing. For instance, in the computational wind engineering (CWE) literature there is substantial caution around numerical analysis, namely for Reynolds-averaged Navier-Stokes (RANS) and to a lesser extent large-eddy simulations (LES) (Stathopoulos, 1997; Bitsuamlak, 2006; Dagnew et al., 2009; Menicovich et al., 2002). However, architects are increasingly getting involved with analysis, where concerns over accuracy are less paramount since demand is typically for relative scenario comparison or general flow behaviour (Lomax et al., 2001; Malkawi et al., 2005; Chronis et al., 2012).

The tall building typology has been identified as a focal area here for a number of reasons. Firstly, as height increases so too do the wind forces (along with seismic and gravitational) which has consequences on facade panelisation and structural efficiency, amongst others. We can construct a simple motivational argument to say that increased external wind force requires more opposing force, i.e. more structure, more materials, larger cores, less letable floor space, less revenue etc. Therefore there is a need to consider the aerodynamic form of these buildings as they increase in height. Secondly, the trend for tall buildings is to build them as high as (contextually, economically and structurally) possible, necessitating cutting-edge design and construction technologies (CTBUH, 2012). Thirdly, tall building form lends itself well to parametric design as there is often a high degree of vertical logic that can be expressed neatly with mathematical expressions (this generalisation is at least more true than for shorter buildings). Given this, it is possible to easily generate a procedural, or generic, tall building model that, with a relatively small number of parameters, can represent a large number of potential designs. This becomes useful when the objective is to sample the typological space of potential buildings, which will be discussed in the methodology.

We present a novel approach to predict wind pressure on tall building models for early-stage generative design exploration and optimisation (exploration as the non-discrete parametric equivalent of tinkering, and optimisation as the single- or multi-objective directed design space search requiring iterative testing and evaluation). The method provides fast surface pressure data with the conventional visualisation, reducing performance feedback time whilst maintaining verisimilitude.

This is achieved through the use of a machine learning algorithm, trained on a pre-computed set of CFD simulation data. *ANSYS CFX 13.0*, a commonly used solver in engineering practice, was used for steady-state RANS with a k-E turbulence model. The learning technique is grouped with artificial neural networks (ANN), support vector machines (SVM), and random forest (RF) decision trees, in that there is a training set of cases from which generalised rules are generated (Duffy, 1997). The term machine learning stems from the fields of computer science (Mitchell, 1997) and artificial intelligence (Samuel, 1959), but in statistics is referred to as regression and in engineering as function approximation or surrogate modelling. Once trained, this enables us to provide a new test case and make a prediction of the outcome. Inductive reasoning, epistemologically, means constructing generalisations from specific information, as opposed to deductive reasoning where small details are construed from generalisations. The fundamental outcome of this learning approach is therefore a continuous output response allowing interpolation and extrapolation between cases that have not been explicitly simulated. In doing so, we are essentially moving the simulation time from the front-end to the back-end of the process where more time is available for pre-computation.

The following section provides a review of relevant literature in the generative, performative design of tall buildings, wind modelling methods, speed-accuracy tradeoffs, incorporation of learning in design, concluding with a problem-solution hypothetical argument positioned in this state of current literature. The subsequent structure of this paper will describe the methodological approach in general terms, and results are presented from a series of experimental case studies of increasing complexity from trivial to practical. The conclusions, further work and the paper as a whole are positioned within the scope of ongoing research.

LITERATURE REVIEW

Tall Buildings

Tamura et al. (2009; 2010) and Tanaka et al. (2012) acknowledge the increase in tall building complexity beyond the traditional extruded rectilinear form. We are now seeing more unconventional free-style forms derived from the architect's use of more advanced modelling software. These new complicated sectional shapes that may vary with height, can actually provide better aerodynamic performance by disrupting, or 'confusing', vortex shedding and thus reducing crosswind response. Benefits can also be found in more subtle manipulations such as corner chamfering or cutting, and by creating voids, or porous regions, near the edges.

Despite rapid advances over the past century, this emerging generation of skyscrapers poses new challenges for wind engineering. Irwin (2009) discusses a number of these, such as the impact that aerodynamics have on construction cost. Since the structure itself is a large proportion of the cost, and as for tall buildings the wind is the governing lateral load, there are significant benefits to be had from reducing wind loads. This also has the effect of reducing lateral motions that can potentially cause occupant discomfort. He also suggests that shape aerodynamics must be proactively considered, and iteratively optimised, early on in the design. With the new generation of super-tall towers over 600m it is simply not possible to ignore the wind performance. He quotes a designer of the Burj Khalif, saying *"we practically designed the tower in the wind tunnel"*, and were therefore able to produce an extremely efficient aerodynamic shape that enabled the height with reasonable structural systems and costs, and without any damping system.

The increase in the use of parametric CAD softwares has seen a rise in the last decade namely with the release of *Bentley GenerativeComponents* and *Rhino Grasshopper*, plus more generally with the increased adoption of scripting. These allow the user to create parametrically associative relationships related to geometry. The extension of this idea is to use rules to define the parameters, or where these rules can be related to the performance of a model component the geometry is directed by some evaluative metric. Certain metrics can be calculated quickly without problem, but if the calculation takes time it becomes obstructive to the modelling process. We adopt the premise that it is better to have a broader range of lower resolution data rather than a limited amount of exact data.

Speed-Accuracy Tradeoffs

Speed-accuracy tradeoffs (SATs) show that response accuracy generally increases with response time, i.e. taking more time to make a decision results in a better decision. Biological examples have been noted by Chittka et al. (2009), who explains that *"when it takes a long time to solve a difficult task, and the potential costs of errors are low, the best solution from the perspective of an animal might be to guess the solution quickly, a strategy that is likely to result in low decision accuracy."* The two extremes can be called impulsive and reflective. This provides a neat analogy for performance analysis in design where it is necessary to consider what the application of the simulation tool is, and the consequent risks, before deciding a suitable accuracy.

Crucially though, and in conjunction with this reasoning, Burns (2005) demonstrates that making more decisions with more mistakes (fast and inaccurate) results in better overall performance (with bees, more nectar collected) than the more fastidious (slow and accurate). Defining accuracy as the proportion of choices that are correct, this highlights that accuracy should not be confined to the immediate task, i.e. simulation accuracy, but to the larger one of improving building performance (Figure 1).

Response time is critical for performance-driven design and SATs must be considered when developing early stage tools for when large-scale decisions are made. Performance information is often scarce at this stage and iterative decisions must be made quickly, necessitating fast response times in sync with the project cycles. The development of CFD models have been focused over the past decades on improving accuracy, and computational time is optimised by specific software vendors after-the-fact, with little thought given to the accuracy required by the user. In contrast, recent developments in computer graphics have started with the desired accuracy (believable) and speed (real-time) in mind, with successful results.

In the design context, CFD can typically be used for a number of purposes: analysis of internal air movement, pollution dispersion, noise propagation, pedestrian comfort in urban environments or tall building aerodynamics. As mentioned previously, it is the last that is the focal application here, especially for early design stages. There is a paradox here,

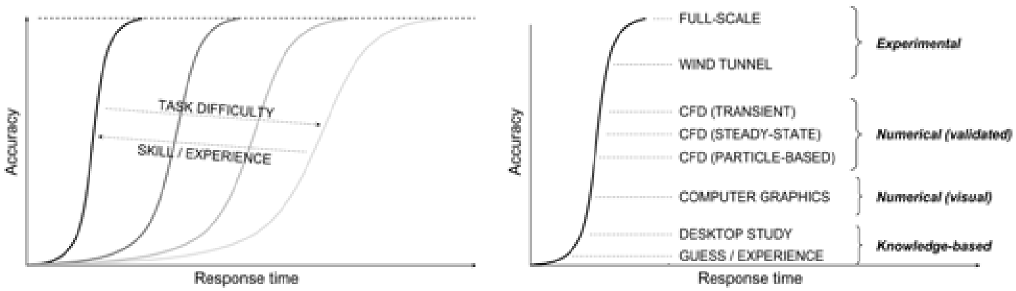

Figure 1
(Left) SAT for various task difficulties and skills; (Right) Notional positions of different modelling methods on SAT.

in that the most complex flow types (bluff bodies) and therefore most computationally intensive, need to be modelled in a scenario where fast results are required. The numerical method must be as accurate and fast as possible. In fact, the conclusion is reached that the fastest method has poor accuracy and the slowest the best accuracy (as would be expected, considering the speed-accuracy tradeoffs mentioned earlier). There is general agreement between (Lomax et al., 2001) and (Chronis et al., 2012) that the *"level of accuracy of a CFD simulation needs to be compromised with the turnaround time requirements of its application."*

Lu et al. (1991) describe the same issue in mechanical engineering where slow but accurate simulation makes interactive decision making impossible, when only quick estimates are desired at early stages. It is only towards the final stages of design, *"when the engineer has converged to a small region of decision space, more accurate simulations are needed to make fine distinctions."* The problem has therefore been present since the early 90s, but as a solution they propose integration of simulation, optimisation and machine learning.

Inductive Learning in Design

Our approach is supported by Samarasinghe (2007), who identifies the best solution to predicting system behaviour through observational data. This is necessary when there is little or no understanding of the *"underlying mechanisms because of complex and non-linear interactions among various aspects of the problem."* Extracting these complex relationships is often difficult since the systems are typically natural, and therefore can have randomness, heterogeneity, multiple causes and effects, and noise. Even when they are successfully extracted, they may be beyond our understanding and are held as intractable computational functions or data structures. Hanna (2011) tests the hypothesis that it is unnecessary to have any understanding of this underlying system behaviour, but rather it is possible to make predictions about the system simply by making observations. This is demonstrated by learning the structural behaviour of system components and applying them to larger-scale scenarios.

Graening et al. (2008) propose a method that allows the extraction of comprehensible knowledge from aerodynamic design data (jet-blades) represented by discrete unstructured surface meshes. They use a displacement measure in order to investigate local differences between designs and the resulting performance variation. Knowledge, or rule, extraction from CFD data is primarily used to guide human- centred design by improving understanding of the system's behaviour, whether it is for jet turbine blade optimisation or architectural design. Whilst the connection between local geometric features and surface pressure has been extended and changed here, and used for a different application, this work is a close precedent.

Problem Hypothesis

It is argued here that approximations of CFD simulations can be made with machine learning regression, using geometric shape descriptors as the learn-

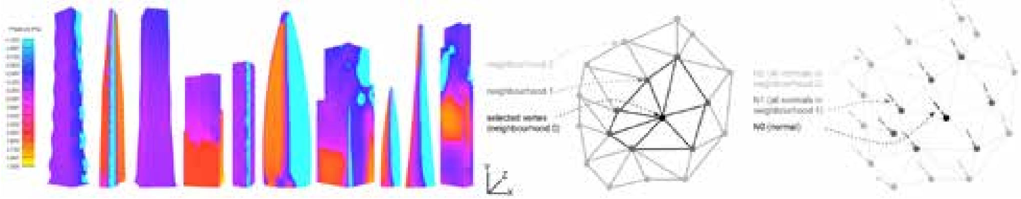

Figure 2
(Left) Examples of evaluated procedural models in the training set on Case 4; (Right) Mesh feature extraction.

ing features. The entire evaluation process can be broadly split into five key work areas: i) procedural geometry generation; ii) batch simulation; iii) shape feature generation; iv) machine learning training; v) prediction and visualisation. Feature generation is essentially the core of the process since the solution depends heavily on geometric description so as to define surface pressure as a function of it. We hypothesise that surface pressure distribution arising from wind flow around tall buildings can be learnt and predicted with an accuracy appropriate to early stage design (feedback from practice indicates <20% error) using shape feature description. It can be shown that it is possible to combine, with an acceptable error, methods that have the separate contradictory objectives of predictive accuracy and speed.

METHODOLOGY

Data Set Generation: Procedural Modelling

The parametric model was created in *Bentley GenerativeComponents*. The goal was to create a generalised tower model, with the two properties of minimising the number of parameters used whilst maximising the design representation potential, i.e. the number of possible buildings it could create. This is important when considering optimisation or exploratory design space searches to avoid the curse of dimensionality. This means that as the number of variables increases, the design space increases exponentially by n^D, where n is the number of samples taken per parameter and D is the number of parameters, or dimensionality. There is therefore clearly a compromise to be made between model efficiency and representability.

The geometry for the training set was generated using a procedural tall building model with a select number of key parameters (Figure 2). There are in fact three separate topologies in the procedural model with their own parameters, since it is difficult to incorporate the entire design space with one parametric logic (Park et al., 2004; Samareh, 1999). Using the unstructured triangulated surface mesh from these means we are not limited by a single parametric topology in the learning phase of the method (Graening et al., 2008). Local surface-mesh shape characteristics are used as input features to the learning algorithm instead of the design parameters, avoiding reliance on any one parametric model definition.

Simulation Method

An established solver, *ANSYS CFX* 13.0, was used throughout to run the RANS steady-state simulations, with a k-ε turbulence model as it is regarded as the most robust. Each simulation, depending on the complexity, requires up to 60 minutes to converge (on a 2.66GHz i7). Solver convergence is reached when residuals fall below a minimum of 1^{-6}, typically at around 100 to 200 iterations. The number of cells in the tetrahedral meshes varies between 0.8×10^6 and 1.5×10^6 depending on the geometry, with prismatic expansion on surfaces 3 cells deep and a minimum cell size of 0.1m. The wind was applied at an upstream inlet, with a reference speed (U_r) of $1ms^{-1}$ at a reference height (Z_r) of 10m. The most commonly used distribution of mean wind speed with height is the 'power-law' expression:

$$U_x = U_r \left(Z_x / Z_r \right)^{\alpha} \quad (1)$$

The exponent α is an empirically derived coefficient that is dependent on the stability of the atmosphere. For neutral stability conditions it is approximately 0.143, and is appropriate for open-surroundings such as open water or landscape. Future work will include a wind profile that takes surrounding surface roughness, or context, into account, as well as potential wind direction change with height.

Shape Features and Learning

This method creates a definition for the pressure at a point on the model as the function of a local geometric description. To describe a simple example of the process: there are N models of a cuboid with various orientations; each is evaluated, and the pressure P is extracted at M points over each model; for every M, a shape descriptor X is calculated, such as the vertex height, normal components, curvature, etc; this gives a set of geometric characteristics, and a corresponding pressure value; these sets of P(X) are used as the training data. Pressure distribution is predicted from these geometric descriptors alone meaning the selection is critical. A sensitivity analysis has been conducted with a variety of descriptors to determine suitable representation, details of which are not included here. When a new case is presented, the shape descriptors are calculated and used to make a prediction of P. The feature definition for point pressure in $\mathbf{R}^{22}$ vector space used throughout the following is:

$$P\,(Z, N_{(x,y,z)}, N\sigma^{1\text{-}5}_{(x,y,z)}, U_{(x,y,z)}) \quad (2)$$

For a specific model vertex, P is the surface pressure, Z is the height, $N_{(x,y,z)}$ are the normal components, $N\sigma^{1\text{-}5}_{(x,y,z)}$ is the standard deviation σ of normal components of cumulative mesh neighbourhood rings 1 through 5, and $U_{(x,y,z)}$ are the normalised model position components. The extent of the neighbourhood curvature can be extended beyond 5 rings, within computational resource limits. The definition in Equation 2 gives 22 inputs and 1 output feature to train the learning algorithm for all cases described below.

For the Orientation, Height and Topology cases, an Artificial Neural Network (ANN) was used, with a 70:30% split of the provided data to training:validation. For the first two cases, separate sets constituting entire models were also held back for testing, i.e. training was at 15° and 20m intervals respectively. For the third case, there was no extra test set but the whole was split 70:15:15% to training:validation:test. Validation data is to check for convergence during training. For the fourth case, training data was from the procedural tall building model and test data from another set of real buildings. In this case, a Random Forest (RF) algorithm was used instead as it provided better results for the more complex problem. Further work is needed with both methods to understand their applicability to certain tasks, however it is known that the RF is better with noisy data sets than the ANN. Training set sizes and summary results are given in Table 1, and computation times are given in Table 2.

RESULTS

Cuboid Orientation

The first and most simple test is the rotation of a cuboid, of width and depth 10m, and height 50m. Simulations were run at 5° intervals from 0 to 85°, and the ANN trained on 15° and tested at 5° intervals. The sensitivity analysis here varies the number of training samples and measures the standard deviation, σ, of the difference between simulation and prediction. Figure 3 (left) shows the error σ against orientation for various set sizes (bold vertical lines are training intervals of 15°), (centre) the training regression of the entire set, and (right) the prediction error for an orientation of 25°. With less training data, it can be seen that error is highest around 45° when flow bifurcations (regime change) occur, although this is negated with sufficient data.

Cuboid Height

Secondly, a parametric cuboid was created with width and depth 10m, and height varying from 10 to 100m in 5m increments. Figure 4 (left) shows the variability when trained on 10, 20, 30 and 45m intervals, and (right) the prediction error for a height of 25m when trained at 20m intervals.

Table 1
Summary of minimum and maximum error standard deviations (% over test case pressure range).

Case	Min σ Error (%)	Max σ Error (%)	Training Set Size
Orientation	1.2 (55°)	1.6 (10°)	110000 (15° training intervals)
Height	0.7 (10m)	2.0 (50m)	44720 (20m training intervals)
Topology	1.8 (5 Edges)	3.5 (0 Edges)	50000
Real	4.8 (Bank of China)	18.3 (Euston)	100000 (Procedural training)

Table 2
*Summary of time (seconds) required for each case, split into Training (one-off back-end time) and Prediction (front-end time). Mean feature generation time is 0.085s/vertex. *Mean over all test set. †After down-sampling.*

Case	Train Sim.	Train Feat. Gen. †	Train	Predict Feat. Gen. *	Predict *
Orientation	21600	9060	2600	1540	< 0.1
Height	18000	2370	720	620	< 0.1
Topology	32400	4670	1060	1750	< 0.1
Real	2160000	12000	620	720	< 0.1

Topology
Here the number of edges was varied from 3 to 10, with 0 (circle), diameter 10m and height 50m. Instead of keeping a complete model separate for testing as in the last two cases, here all cases were used but only a fraction of the total data set was used. This is varied in Figure 5 (left), with a training set ranging from 10000 to 50000.

Tall Buildings
In the final case, training data was collected from simulations of 600 procedural tall building models, with a total of over $4x10^6$ shape features extracted. This was down-sampled to 10^5 by removing features in close proximity to reduce training time. The test set contains 10 real tall buildings from around the world, selected for their range of unique architectur-

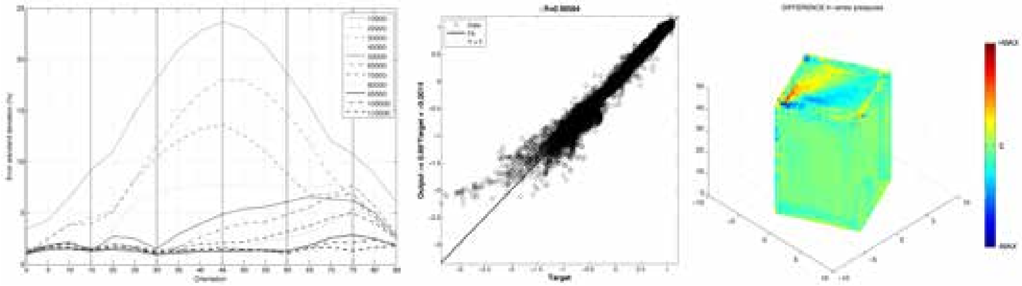

Figure 3
(Left) Orientation vs. Error σ %; (Centre) Training set regression, R=0.99564; (Right) Prediction error (25°).

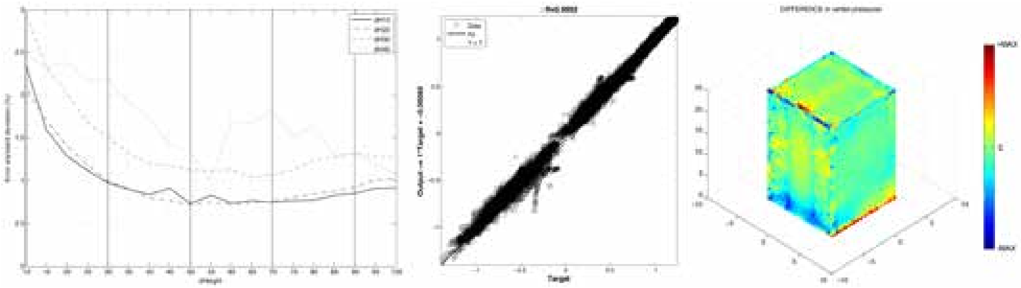

Figure 4
(Left) dHeight vs. Error σ %; (Centre) Training set regression, R=0.9992; (Right) Prediction error (25m).

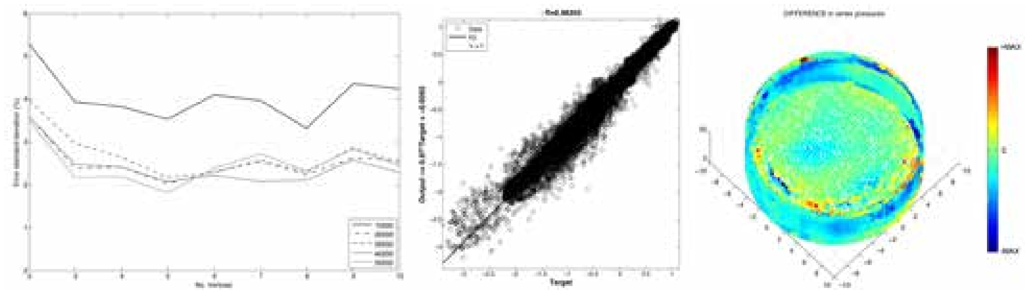

Figure 5
(Left) No. Edges vs. Error σ %; (Centre) Training set regression, R=0.98355; (Right) Prediction error (n0).

al characteristics. Figure 6 shows predicted surface pressure distribution in the top row, and the error distribution for the set in the bottom row. The pressure range (-5.5 to 2.0 Pa) was taken over the entire test set, as was the absolute error range (0 to 65.2%). The error distribution is shown in Figure 7 (right), which fits a Gaussian normal distribution. Error percentiles: 99^{th} = 35.7%, 95^{th} = 20.0%, 90^{th} = 13.0%, 75^{th} = 6.1%. That is, 75% of the test features have an error below 6.1%.

CONCLUSION

The results show that it is possible to achieve a relatively small prediction error (Figure 7 and Table 1) for less time (Table 2), with the methodology and constraints described. These prediction errors are necessary for the compromise in avoiding considerably intensive CFD simulation. Traditionally, for every individual CFD simulation the process can take a minimum of 1 hour, compared to our methodology that has a total front-end prediction time of under 12 minutes (for feature generation and prediction) and a back-end, one-off training set simulation time of 600 hours (for the real case). Once trained, an unlimited number of predictions can then be made.

Whilst these preliminary results are outside the rigorous accuracy necessary for final engineering analysis, they are within the boundaries acceptable

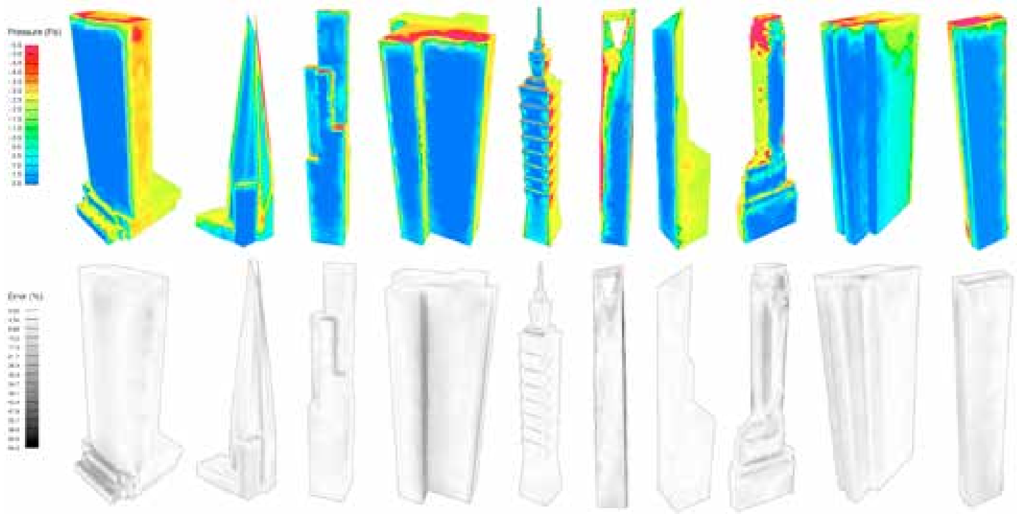

Figure 6
(Upper) Predicted pressure, Pa; (Lower) Error, %. Pressure range is the min. and max. of the entire set for comparison, the error range is absolute max. error of the set (65.2%). (Left to right) (1) Metlife Building, NYC; (2) The Shard, London; (3) Willis Tower (Sears), Chicago; (4) Euston Tower, London; (5) Taipei 101, Taiwan; (6) Shanghai World Financial Centre; (7) Bank of China; (8) Exchange Place, NYC; (9) Frankfurter Buro Centre, Frankfurt; (10) Washington Street, NYC.

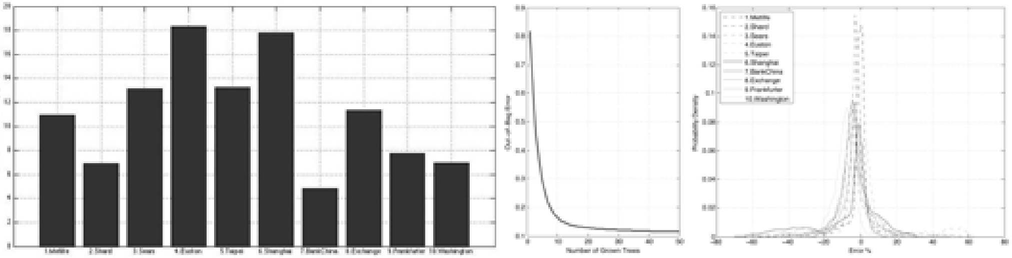

Figure 7
(Left) Error σ % for each case; (Centre) Random Forest learning convergence; (Right) Error probability density.

for early-stage concept design for tall buildings, where interactive response time is a significant consideration. The prediction accuracy and response times achieved are promising for further work given the well-known complexities of fluid behaviour.

The next stages of the work are to consider time-dependent simulations to fully consider the approximation of turbulence, vortex shedding and gusts, as well as interference from complex urban contexts on boundary conditions, and further improvement to the shape feature selection and generation time.

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Adaptive Fluid Lens and Sunlight Redirection System

Exploring a novel way of redirecting and altering sunlight in large span roofs

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Abstract. *The paper describes a novel system to alter and redirect sunlight under large span roofs with the help of a fluid lens system. Focus lies on the computational design, testing, measurement and evaluation of the performance of a physical prototype.*
Keywords. *Daylight; large span roofs; optics.*

OBJECTIVE

The general aim of the presented research is to develop a design methodology with the help of computational tools and prototypes in order to be able to design adaptive daylight systems in large span roofs under consideration of user and functional requirements and respectively daylight performance aspects. Adaptive solutions for vertical facades with relatively small rooms and individual requirements of the inhabitants in form of e.g. louvers are well researched and applied. In the case of large span roofs where the horizontal part of the envelope exceeds the vertical one for admitting light, the design requirements and parameters for daylighting are different. Here collective lighting requirements and adjustability for a higher amount of inhabitants, diversity of functions, larger spatial entities and the geometrical relations between sun path and general roof alignment towards the zenith play a major role. However not only quantities of light according to regulations or qualitative aspects in form of visual comfort but also energetic aspects in terms of heat gains are part of the design and research scope. The research on the adaptive fluid lens and sunlight redirection system described here is one of the case studies being developed within the framework of an ongoing PhD research at TU Eindhoven. In this specific case the objective is to find a way to capture and utilize sunlight to be used under a large span, horizontal roof in order to be adaptively redirected where needed and dynamically treated or altered in such a way that it can fulfill various functional aspects (Figure 1). This horizontal "window" has to continuously mediate between the dynamic yet known path of sunlight in relation to the location and the possible change of interior use or functionality and thus lighting requirements.

PRINCIPLE

The adaptive lens and sunlight redirection system consists of two major components (Figure 2). Firstly

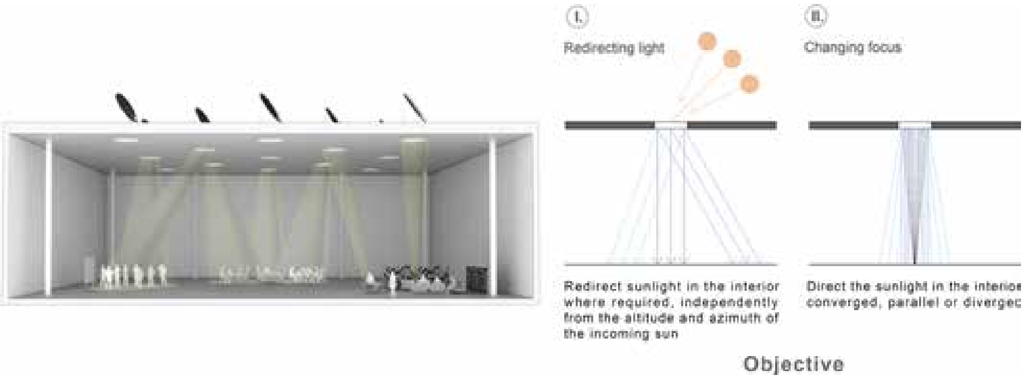


Figure 1
Objective of the adaptive fluid lens and sunlight redirection system.

a set of mirrors which as a whole orient themselves towards the general horizontal sun direction (azimuth) and individual rows of mirrors which are rotated in the same angle according to the sun altitude. The altitude orientation is done in such a way that the incoming sunrays are reflected downwards into an aperture which houses the adaptive lens. The lens itself consists of a transparent horizontal lower surface, a casing and on top an elastic deformable and transparent membrane. By changing the internal volume via pumping a clear and transparent liquid, the shape of the membrane can be changed from concave to convex and continuously all the stages in between, thus being able to diverge or converge direct light according to Index of Refraction (Taylor, 2000) and Snell's law (Taylor, 2000).

DESIGN APPROACH

The design approach consists of five steps. (1) Physical principles (2) Associative 2-D and 3-D models (3) Simulation (4) Prototype (5) Prototype measurements and evaluation

Step 1: Physical principles

In order to apply physical principles like Snell's law of Refraction or Fresnel's equation for reflection and transmission (Bennett, 1995) several associative files were set up in the Rhino/Grasshopper environment in order to see the effects of light refraction, transmittance, absorption or reflectance of various geometry/material combinations and evaluate the possibilities for sunlight redirection and alteration.

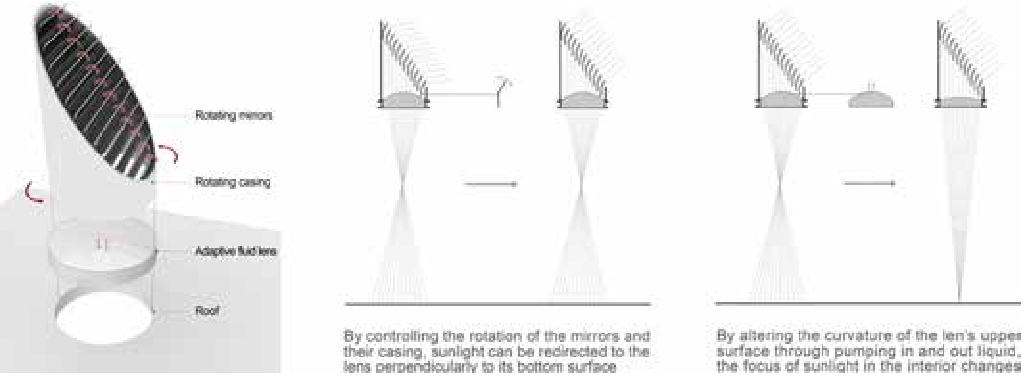


Figure 2
Description of the proposed system.

Table 1
Sun altitude occurrences for Munich.

Percentage of the day that the altitude of the incident sunlight is at a specific angle range

2013	Munich	PERCENTAGE												TOTAL (%)	
	Date	21-Jan	21-Feb	21-Mar	21-Apr	21-May	21-Jun	21-Jul	21-Aug	21-Sep	21-Oct	21-Nov	21-Dec	Jan-Dec	
	DST	off	off	off	on	on	on	on	on	on	on	off	off		
ALTITUDE ANGLE	< 0°	62.50	56.25	50.00	41.67	35.42	34.38	36.46	42.71	50.00	56.25	63.54	65.63	49.57	-
	0°-10°	11.46	9.38	8.33	9.38	10.42	8.33	9.38	8.33	8.33	9.38	10.42	12.50	9.64	19.10
	10°-20°	15.63	10.42	8.33	8.33	8.33	10.42	8.33	8.33	8.33	10.42	16.67	21.88	11.28	22.38
	20°-30°	10.42	15.63	10.42	8.33	8.33	8.33	8.33	8.33	10.42	16.67	9.38	0.00	9.55	18.93
	30°-40°	0.00	8.33	12.50	9.38	8.33	8.33	8.33	9.38	12.50	7.29	0.00	0.00	7.03	13.94
	40°-50°	0.00	0.00	10.42	11.46	9.38	8.33	9.38	11.46	10.42	0.00	0.00	0.00	5.90	11.70
	50°-60°	0.00	0.00	0.00	11.46	12.50	10.42	11.46	11.46	0.00	0.00	0.00	0.00	4.77	9.47
	60°-70°	0.00	0.00	0.00	0.00	7.29	11.46	8.33	0.00	0.00	0.00	0.00	0.00	2.26	4.48

Data collected from: Solar elevation angle (for a day) calculator, http://keisan.casio.com/exec/system/1224682277

Hours of sunshine per day

Munich	HOURS OF SUNSHINE											
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
h. per day	1.97	3.00	4.13	5.23	6.42	6.97	7.65	6.87	5.77	4.16	2.30	1.58

Data collected from: Climatedata.eu, http://www.climatedata.eu/climate.php?loc=gmxx0087&lang=en

Step 2: Associative 2-D and 3-D models

Snell's laws is most relevant and was translated into associative 2-D sectional drawings of a light converging/diverging lens and a mirror system in order to understand the capabilities and performance of the proposal under changing light directions. In this initial step an adaptive lens system was set up which is able to change the radius of an upper lens and Index of Refraction of the contained liquid according to material properties of existing fluids and Snell's law in order to focus or diffuse light. Here an array of vectors is refracted within the lens and made visible via a bundle of lines to serve as design and early evaluation tool. The change in altitude angles of the sun leads to a change of the focal point of the refracted light and it showed that the redirection possibilities of a lens are limited. This means in order to keep the light e.g. diverged in terms of a constant area size, the membrane's geometry has to be continuously changed by pumping liquid due to the resulting change of the focal point in relation to the sun's changing altitude. For this fact and the lens' limited possibility of light redirection into the interior a secondary system for light redirection is required. Therefore several options like trapping light by internal reflections (glass fiber principle), a rotatable prism system or plain mirrors were evaluated. The system of rotating mirrors was favored, because this proofed to be more "straightforward" and promising in terms of light redirection under a greater variety of altitude angles. To reduce the height of the mirror system located on top of the lens, an array of mirrors was chosen instead of one larger mirror. This approach poses several challenges in term of overshadowing each other and being able to redirect sunlight in different quantities according to the sun's altitude angle and it turned out that there is no universal system which works equally well in for every sun altitude. Therefore it is necessary to take a closer look at several design parameters and become specific about location, the respective available hours with sunshine, the annual and daily sun path and the prevalence of certain ranges of sun altitude angles and times of occupancy of the building. By matching these parameters it is possible to narrow down the target range of altitude angles where the redirection of sunlight is working a hundred percent. By choosing a design example in Munich and as function a train station which is heavily frequented during the rush hours, lower sun altitude angle ranges, which occur more frequently during mornings and evenings but also during spring, autumn and winter become more relevant (Table 1). By applying the Galapagos genetic algorithm solver [1] to generate and validate variations of the fixed inclination of the whole mirror array, the distance, sizes and amounts of the individual mirrors, a whole set of design solutions is produced which redirects sunlight altitudes perpendicularly to the ground by a 100% within a Δ range of 30° (Figure 3). It is then a

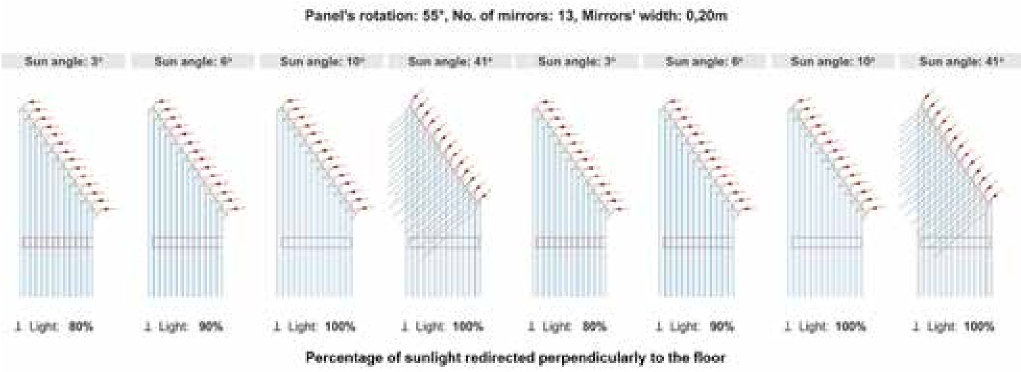


Figure 3
Grasshopper study on the percentage of sunlight redirected perpendicularly to the floor according to the sun altitude.

matter of selecting the configuration which is most suitable for the design task at hand. In the example of Munich, a mirror configuration was eventually chosen which operates perfectly between 10-40 degrees. After evaluating the design principles in the earlier steps associative three-dimensional files were set up to further evaluate the behavior of the lens and mirror system and also to have a geometrical input for later daylight simulation.

Step 3: Simulation

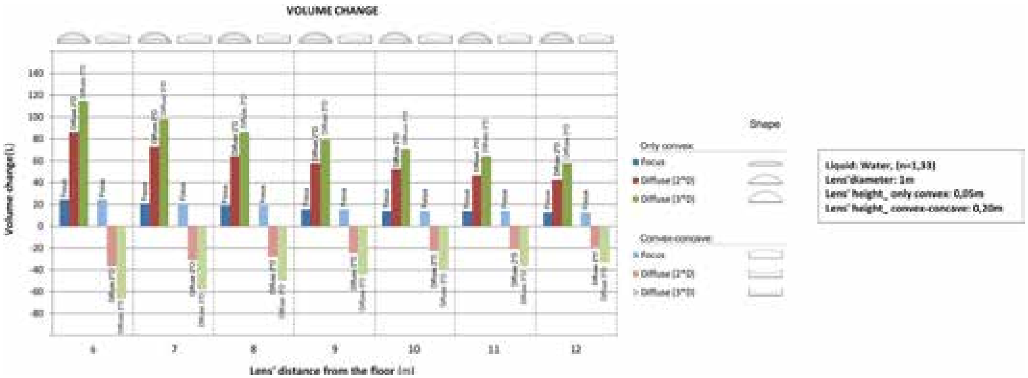
The simulations were done via Diva/Radiance [2] and the VRay renderer [3] also available for Rhino 3D. The Radiance simulation was initially regarded as being important because it is able to show physical values like illumination in lux or luminance in cd/m^2. This would enable to check the performance for actual conditions and requirements as stated in e.g. building codes. However the various simulations done proofed to be not accurate since Radiance for windows is not able to calculate optical effects with dielectric material properties properly (Jacobs, 2012). This has to be done in the Linux environment with the help of a photon mapping module, which was developed by the Fraunhofer ISE [4]. This approach for simulating several different and adaptive geometries and the consequence to manually input the data in Radiance for Linux defies the seamless integration of parametric modelling and simulation. Curiously contemporary render engines such as VRay are able to calculate caustic effects [3] with physically correct material properties and Index of Refraction but are not able to display physical values such as Illuminance, etc. It was therefore decided to design and manufacture physical prototypes for the performance evaluation in accordance with the earlier findings from the associative 2-D and 3-D models.

Step 4: Prototype

During the design process for the prototype, research was done for lens diameters, change of volume and weight on the roof for a 1:1 case (Figure 4). In general it can be said that the higher a roof is situated above ground the less of a shape change in the lens has to occur in order to achieve a desired effect. By studying theses parameters it was decided that a lens with a diameter of 1m would be optimal for many applications in terms of weight and required volume change within the lens.

The final prototypes which serve as proof of concept and are used for daylight performance measurements were manufactured in the scale 1:10 (Figure 5). The majority of parts including the mechanical parts like gears and cograil for the sunlight redirection device are made of white ABS plastic and 3-D printed by a Fused Deposition Modeling (FDM) printer. For the mirrors 3M™ Solar Mirror Film 1100 is applied on the rotatable ABS fins. The membrane for the lens is a self-cast and baked Polydimethylsilox-

Figure 4
Volume change required for the convergence and divergence of light in relation to the room height.



ane (PDMS) membrane provided by Michael Debije at Functional Devices research group of the Department of Chemical Engineering and Chemistry at TU Eindhoven. Water with an Index of Refraction of 1,33 (Lide, 2009) is used as optical liquid. Other liquids like colorless and transparent oils which generally have a higher Index of Refraction are also thinkable.

Step 5: Prototype measurements and evaluation

The physical experimentations with the 1:10 scale prototype aimed at testing the performance of the system under clear sky with sun (Test 1-3) and cloudy sky conditions (Test 4) (Figure 6). For the simulation of the clear sunny sky, a Solar Simulator was used, providing directional light, while for the overcast sky, an Artificial Sky Simulator was employed, to achieve diffuse lighting conditions. Through all test series, illumination measurements were done using a Hagner Digital Luxmeter EC1 and lumination pictures were taken with a Canon EOS 60 D and further processed in Photolux 3.2. [5]

Clear sky with sun, Test 1 and 2 set up

The first two series of tests (Test 1 and 2) focused on the performance of the adaptive fluid lens alone under clear sky, supposing an ideal situation of 100% incoming perpendicular to the floor light, which would occur if the sun redirection systems functioned perfectly. To simulate the above, the altitude of the solar simulator was set to a 90° angle. Two different in size closed boxes (Test 1: 0,5*0,5*0,35m,

Figure 5
Aspects of the adaptive fluid lens and sunlight redirecting system prototype in 1:10 scale.

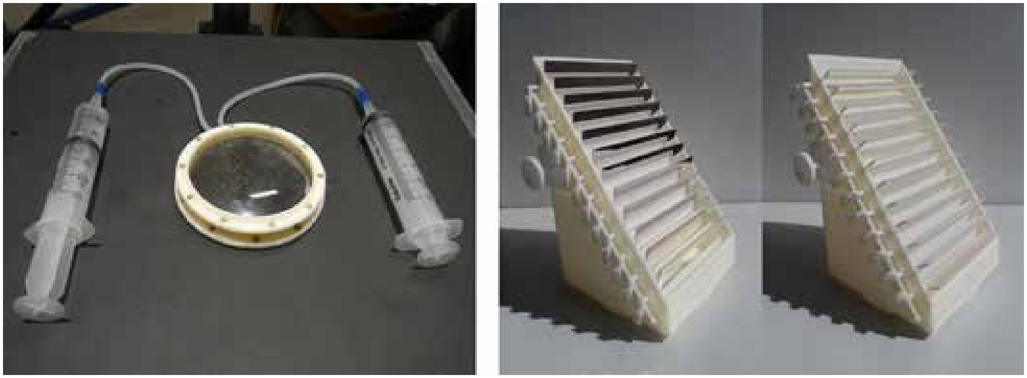


Figure 6
Test settings: From left: Solar Simulator at a 90° altitude (Test 1), Solar Simulator inclined at a 30° altitude (Test 3). Artificial Sky Simulator (Test 4).

Test 2: 0,7*0,7*1m) with a circular opening at the center of their top surface for the 10cm diameter fluid lens to be placed over, were used as room models. Water was pumped in and out of the two syringes connected to the lens, to reconfigure its shape from neutral to convex and concave. These tests approximate the performance of a 1m diameter fluid lens in a 3,5m and 10m high room respectively.

Test 1 and 2 observations and comparison
The tests showed that under clear sunny sky conditions the light is indeed diverged or converged according to the configuration of the membrane and similarly to the predictions from the grasshopper models (Figure 7). Comparing the two room scenarios and scaling up the results to 1:1, it is confirmed that a lens of 1m diameter is more efficient over a 10m high room than a 3,5m room, as previously estimated. To be more specific, in the case of the 1m box, the removal of 55ml of water from the lens in neutral state causes a circular lit area on the floor of 0,46m diameter (concave lens) while the addition of 12ml produce a focal point on the floor of 0,01m diameter (convex lens) (Figure 8). In full scale the values would be 10m, 55L, 4,6m, 12L 0,1m. At the 0,35m high box r, when an almost equal water volume (58ml) is removed from the neutral lens, a lit area of 0,22m is produced. Furthermore, in order to achieve focused light on the floor at a point of 0,005m diameter, 26ml of water need to be added to the neutral lens. In full scale the values become 3,5m, 58L, 2,2m, 26L and 0,05m accordingly. In general, at the con-

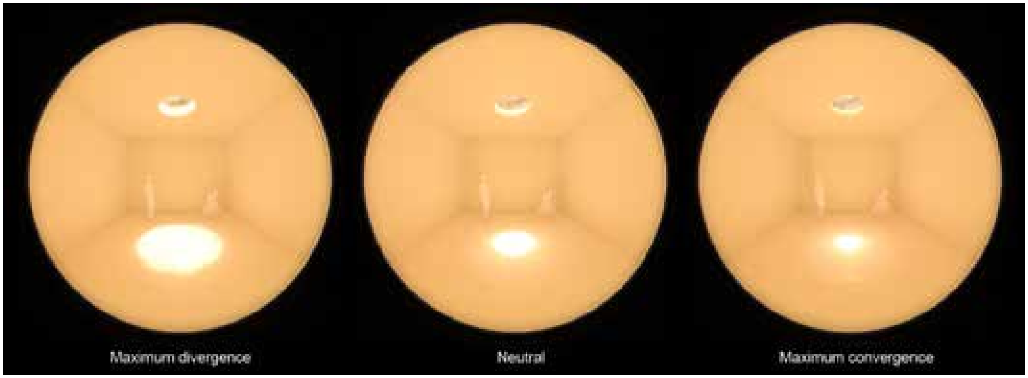
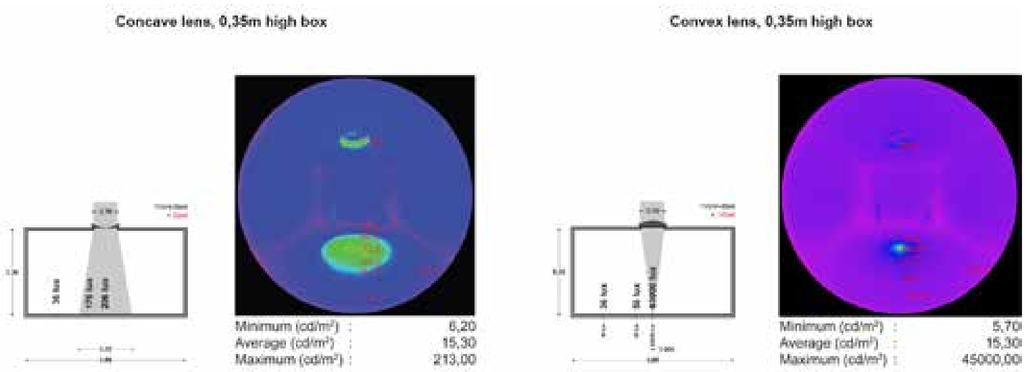


Figure 7
Differences in the quality of shadows from the concave to the convex mode of the adaptive fluid lens.

Figure 8
Test 1: comparison between the diverged and converged mode.



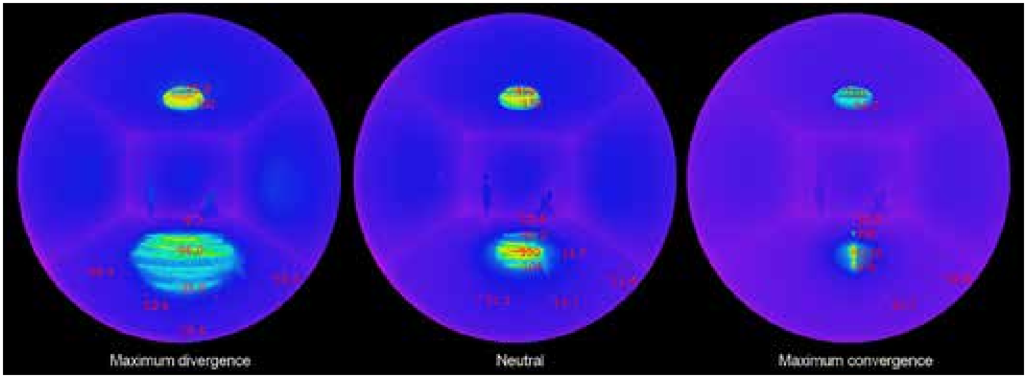
cave mode, the lens is acting as a spotlight spreading out the received sunrays. The light hitting the floor surface and reflected by it causes the formation of soft shadows by the scaled human figures placed at the periphery inside the box.

Considering the focused mode, the flux density at the center of the floor surface (63.000lux for Test 1 settings) is excessively high in comparison to the density measured at the periphery (36lux for Test 1 settings). Given the fact that in Test 1 the sun simulator produces a value of 908lux at the floor center and scaling up the findings, we can assume that on a clear sunny day in summer where 100.000lux reach the ground (Flesch, 2006), the flux density will be 6.940.000lux at the center and 4.000lux at the periphery. Such concentration of light is responsible for high contrast ratios in the room that not only exceed the acceptable contrast thresholds for visual comfort but also surpass the 1:1000 ratio which is the range of brightness the human eye can perceive (Green et al, 2008). The most extreme converging mode might not be applicable for daylighting. However other uses are possible as described in the outlook section of this paper.

Test 3 set up

Test series no. 3 examine the effectiveness of the sunlight redirection system on a clear sunny day (Figure 9). For these tests, the 0,5*0,5*0,35m box was used as a room model and the solar simulator was set at 30° sun altitude, where the sunlight redirection system is expected to be 100% efficient accord-

Figure 9
Test 3: different lens configurations.



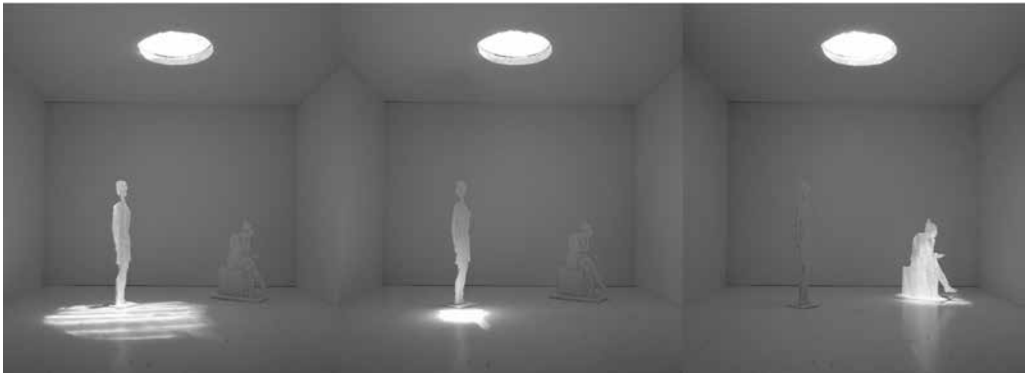


Figure 10
Adaptive daylight in the interior.

ing to the Grasshopper/Galapagos models. The system was placed over the fluid lens at the top of the box and the mirrors were rotated as such, to direct the received light perpendicularly to the ground.

Test 1 and 3 observations and comparison

Although the sunlight redirection system manages to redirect the light perpendicularly to the ground, the system in combination with the lens do not succeed in bundling all the rays in one focal point but in fact a linear series of focal points is noticed. This deviation is caused by imperfections of the mechanical system controlling the rotation of the mirrors. It can be derived that even minor deviations of the mirrors from the correct inclination can direct the light in a non-desired direction as well as light scattering is further enhanced if the film is not evenly applied over the ABS lamellas. The imperfections at the rotation mechanism are also responsible for the presence of more accentuated shadows on the floor cast by the row of mirrors. Minor shadows are of course expected at the neutral and diverging modes of the lens due to the thickness of the mirrors but not to the observed extent.

Light redirecting possibilities

The prototype showed that initial expectations in terms of light redirection capabilities of the systems were by far exceeded (Figure 10). In the Test 3 configuration it was possible to redirect light within the sun's azimuth alignment until reaching the wall. In the other direction it was possible to reach 90% of the space (0,5m*0,5m) with the spot. The Test 2 configuration in combination with the redirection device did not fit under the sun simulator. However it should be noted that, the higher the ceiling is located above ground, the more the range and performance is increased in terms of light redirection. Due to the height of the redirection device itself the area of illumination is more reduced the further the light beam is astray from the vertical redirection configuration. Furthermore it will also be interesting to see the interaction and lighting design possibilities of several devices together.

General findings regarding the fluid lens under clear sky conditions

The light and heat absorption by the water volume is another issue worth to be discussed as during clear sky conditions, the lux value on the floor surface under the opening is reduced in both Test series 1 and 2 by 31% when the lens at its neutral state is placed over the opening. The Beer-Lambert Law explains the logarithmic relationship between the transmission of light through a substance, the thickness of the medium and the wavelength of the light, proving that the intensity of light decreases exponentially with the increase of the water depth (Ryer, 1997). Taking into account that the light absorption coefficient of water for violet light (380nm wavelength) is 0,00011cm^{-1} and for red light (725,5nm wavelength) is 0,01678 cm^{-1} (Pope et al, 1997) and by applying the Beer-Lambert law for a water depth of 1,4cm (water depth at the neutral state of the prototype), it can be concluded that 0,035% of violet light and 5,26% of red light will be absorbed by the water volume. Considering the full scale lens, the occurring light absorption will increase due to the 10 times higher water depth. Calculations show that 0,35% of violet light and 41,77% of red light will be absorbed by the water volume. Moreover, due to the selective color absorption property of water, the light exerting the lens will have a slight blue hue.

In addition, the light absorption coefficient of water for wavelengths of 1.000nm to 1.000.000nm ranges from 0,339 cm^{-1} to 128,2 cm^{-1} meaning that water is strongly absorbing infrared light (Zolotarev et al, 1969). Of the radiant energy emitted from the Sun, approximately 50% lies in the infrared region (Fu, 2003). This energy is to be perceived as thermal energy, absorption of the infrared light leads to the reduction of the amount of heat entering the room from the lens. Due to the high specific heat index of water, the lens is expected to act as a thermal mass that absorbs, stores and releases heat where the penetration of heat is delayed.

Cloudy sky

Test series no.4, conducted in the Artificial Sky Simulator, study the performance of the system in the worst case scenario, that of a cloudy winter day. For these tests the 0,5*0,5*0,35m box was used first with the fluid lens alone at its top opening (Test 4A) and then with the sunlight redirection system placed over (Test 4B). According to the findings, the incoming light is evenly distributed rather than diverged or converged.

When comparing Test 4A and 4B, we conclude that the sunlight redirection system is reducing the amount of incoming light by 47,8% at the area under the opening (flux density is reduced from 53lux to 28lux) and by 57,5% at the periphery of the space (from 46lux it becomes 19lux). To scale up the measurements to real overcast conditions, we consider a typical flux density at ground level on a cloudy winter day of 4000lux (Flesch, 2006) and relate it to the 962lux measured outside next to the box. This results in 220lux at the center of the floor area and 191lux at the periphery when only the fluid lens is present, and in 116lux and 79lux respectively when the sunlight redirection system is added.

CONCLUSION

Assessment of the combined system

The physical experimentations prove the ability of the system to quickly adapt not only in order to converge/diverge the sunrays but also to redirect the incident light according to the needs of the interior space over almost the whole floor surface. The system successfully proved to be able to function as a daylight spotlight which can adaptively react to the moving sun position as well as interior lighting requirements. The changes between different modes occur gradually rather than abruptly and thus are not disturbing to the user.

It is however concerning the high contrast ratio observed in some of the tests and the probability of glare needs to be evaluated. Also the illumination of the interior when more than one adaptive sunlight redirecting modules are installed in proximity has to be determined. The performance under worst case, cloudy sky conditions appears to be sub optimal and this would either determine a certain amount of lenses required on the roof or would suggest an application at a location with a high amount of sunny hours. By applying the system at the more southern hemisphere location it would not only be more effective in terms of direct sunlight but the building would also benefit in terms of heat absorption and reduced heat gain. In general the system is useful for interiors which require directed light and are not affected by contrasts. This could be suitable for atria, large markets, shopping malls or restaurants to place dynamic daylight accents and highlight certain spots. If a more even and diffuse light distribution like in train stations, etc. is required an additional adaptive light diffusor has to be thought of.

Simulation versus prototypes

With the current possibility to easily and cheaply manufacture functional prototypes and the ongoing tendency of more, relatively cheap, user friendly but none the less fairly accurate 3-D printing technologies like FDM printers being released on the market there is a great chance that we might face a renaissance of physical testing rather than simulation only approaches.

OUTLOOK

To finalize the research the measured results will be fed back into the digital environment to close the circle but also to have a more complete design tool. In more practical terms sensing and actuation and the digital interface should be thought of as well as more material research for an actual application has to be done. The requirements for a high degree in precision in redirecting sunlight needs to be further considered. The extreme converging mode of the lens and bundling the light into one spot might not be applicable for lighting the interior but could be interesting in combination with photovoltaic as a concentrator system while the space underneath is less frequented or occupied by the inhabitants. The photovoltaic elements could be mounted as a relatively small device close to the ceiling and would therefore not disturb the flow of light otherwise. It would be also possible to employ a more expensive but highly efficient photovoltaic cell since the surface area is small while being more protected from any outdoor influences like dust and rain. Next steps will also include research in smart material application together with the Functional Devices research group of the Department of Chemical Engineering and Chemistry at the TU Eindhoven in order to investigate the possibility to develop a similar functioning system without any moving parts involved.

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Modelling and Simulating Use Processes in Buildings

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Abstract. *In this paper, we propose a new approach to simulating users' behavior in yet un-built buildings. For this purpose, we have developed a model that connects two different representations: a formal representation of the building use, by means of a method borrowed from Business Process Modeling and Notation (BPMN) approach; and a game-engine based 3D virtual environment, where this process is effectively simulated and integrated with some autonomous behaviour of users/agents. The model has been applied to two test cases, where the activities of doctors, nurses, patients, and visitors in different hospitals were tracked, simulated, and reviewed by medical professionals for validation.*
Keywords. *Building use simulation; human behaviour modelling; BPMN; activity-based modelling; building performances prediction.*

INTRODUCTION/RATIONALE

During the design process, architects are asked to predict and evaluate future building performances related to a large number of functional, typology-based and organization-based requirements. To support their design decisions, architects usually rely on functional programs which are interpretations of the requirements of the organization that will occupy and use the building, namely: the main activities of future building's occupants.

In the past, this interpretation process has been mainly supported by normative methods, regulations and general design rules. Nevertheless, the domination of normative approaches has shown its limits in light of increasing complexity of building design and typology, and the intrinsic complexity of human - building interaction (Koutamanis and Mitossi, 1996). As matter of fact, its high level of abstraction is not well-suited to the intrinsic uniqueness and context-dependence of an architectural product. Specifically, basing design decisions on a set of averaged parameters, in the assumption that the building will satisfy future users' needs (Zimmerman, 2003) much like "similar" buildings have done so in the past, often fails when real users, who may differ from the "average" user in many ways, finally meet the building.

Architects' ability to predict in which manner their design will be used, and whether it will match the activities of its intended users, is currently only supported by the architects' own expertise and imagination. Sadly, the consequences are clearly recognizable in reality: too often buildings do not perform as expected after their construction, and sometimes they completely fail to support the activities of the organizations that will occupy them.

The observation and analysis of human behavior in built environments is usually considered the best way to understand and evaluate how a building fits the needs and the activities of its intended users. On this basis, the Post Occupancy Evaluation (POE) paradigm has proposed several approaches and techniques to assess if the project brief has been met (Preiser, 1988). POE approaches have, of course, one major limitation: they can be applied only after the building has been realized and occupied, and at that point it is usually too late or too costly to intervene in order to solve errors, critical failures, and inconsistencies with the needs of users.

In order to overcome this deficiency in the design process, we chose to investigate how to use "virtuality" to actually integrate building occupancy evaluation into the design process, allowing designers to test their decisions before actually entering into the construction phase. In particular, the proposed model focuses on simulation of activities in the built environment, in order to predict how the building will match the functional needs of the organization that will occupy it.

RELATED WORK

Since the inception of Computer Aided Architectural Design, several attempts have been made to introduce the expected users' activities in building representation models (Eastman and Siabiris, 1995; Carrara, Kalay and Novembri 1986; Ekholm and Fridqvist 1996). In such models, however, activities have been explicitly represented in terms of their spatial features - usually relying on the concept of "functional unit" - or implicitly inferred by using sets of functional requirements as criteria for the evaluation of the capabilities of a space (Archer, 1966).

Gradually, research attention in this field has turned from a "space-based" representation of users' activities to a "process-based" representation, considering activities as entities on their own that are clearly distinct from (but connected with) spatial entities (Wurzer, 2010). This new approaches is based on the idea of modelling processes depending on the operational workflows of the organization - or of an organization typology if the specific data are not available - that will occupy the building, and then simulate their execution in the building model (Tabak et al., 2008; Goldstein et al., 2011). This approach has been worthily tested in buildings such as hospitals, offices and airports, where the organizational workflows and the related interactions with the built environment actually drive and heavily influence users' behavior.

Still, some criticisms has been raised of this approach in terms of its ability to realistically predict human behavior in architectural design, since it relies on a rigid, 'functionalistic' representation of operational processes of the organization, usually completely computed before the actual simulation and not adaptable to single users' behaviors and to the overall status of the built environment (what we call 'serendipitous' or 'emergent' activities). This distortion inevitably reduces the ability of these simulative approaches to predict building response to users' needs and activities, and rely instead on architects' imagination and expertise to actually guess in what ways their design will perform after the building will have been occupied.

In the last few years, Agent-Based Modeling approaches have been introduced in this research field, aiming at simulating users' behavior in built environments by developing a series of autonomous entities - the agents - each of whom interacting in an autonomous way with the other users and with the environment surrounding it (Macal and North, 2007). Although Agent-Based Modeling has been successfully applied to simulation of some behavioral phenomena generated by individual actors/agents (such fire-egress and pedestrian movement), it has shown its limitations in simulating agents' cooperation and collaborative activities performing.

AIM OF THE PROJECT

The work presented in this paper aims at developing a different model to simulate users' behavior in buildings, in which the building use representation is still based on a process-driven system, but it is more adaptable both in terms of its activities structure and of users' individual decisions and actions. In order to provide these capabilities, we intervene at two different levels of the model: in the formalization of the building use process, which we define as use scenario, and in the simulation system of the users' behaviour derived by the scenario.

A building use process has a direct correspondence to the way the occupant organization works in terms of operational workflows, procedures and systems of activities (Ekholm, 2001). Based on this assumption, we chose to rely on a modeling approach -the Building Process Modeling and Notation- already developed to represent how an organization operates and to extend it to representing the use process of a building.

The BPMN level, where the use process is formalized, is connected to a 3D simulation environment (a game engine in our case), where the same process is effectively computed, simulated and visualized at the same time. In this environment, Users/Agents are provided with the abilities to autonomously adapt their behavior within a predefined range, depending on the status of the environment model and on the reference process model. In turn, the simulated users' serendipitous actions are fed back into the process model, and can influence it. For example, in the case of a hospital, when a doctor and a nurse are scheduled to check on a patient, but the patient has chosen this particular moment to visit the bathroom, the absences of the patient is fedback to the process model, which defines a different flow of activities for the doctor and the nurse. Likewise, if the paths taken by two agents brings them into geometric proximity, due to the geometry of the building, they may choose to stop and chat, or ignore each other and continue on their predefined missions.

The novelty of this approach lies in making the process execution more flexible and partially adaptable to serendipitous "emergent" activities in real time during the simulation, while in current approaches the activities flow is usually compiled and fixed before stepping into the effective simulation (Tabak 2008). In addition, the proposed model can represent and simulate collaborative, planned activities, such as cooperation among various users when performing their tasks. In terms of usability by architects, planners and clients, the outcome is a simulation/visualization in a 3D virtual environment of how the use process is actually carried out by the building users in the building spaces prefigured by the architect. In this way, it is possible to predict and evaluate the correspondence and the mutual influence between the building and its intended users, and rapidly compare the simulation outcomes of different design solutions and spatial configurations. To test and calibrate the model, it has been implemented to simulate the functioning of two different hospital wards, comparing its output with the real users' behavior.

REPRESENTING BUILDING USE PROCESSES BY MEANS OF BPMN

As asserted by Ekholm (2001), we can look at an organization as a system with relations among its parts whose functioning is actually a process (a sequence of events) derived from performing a series of activities. In accordance with the purpose of our research, we chose to extend the concept of 'system' from the simple organization to the sum of building spaces, activities and actors. The *Business Process Modeling and Notation* (BPMN) approach allows representation of operational processes of an organization in order to orchestrate the activities and the decisions of the different actors involved (White, 2006; Lam, 2012). It provides a representational system that, different from previous approaches, provides at the same time a formalization schema for processes and explicit semantics for its execution/simulation. In particular, it is able to describe different aspects of actors' interaction in an operational process (orchestration, collaboration, choreography, decision points), a feature we consider relevant for the purpose of our research, since it allows formalization of cooperation among different building users during the performing of an activity.

The BPMN formalization is based on a set of elementary entities that can be used to decompose and represent an operational process, the main ones are:

- **Activities**: representation of tasks, works, or operations that have to be carried out or ex-

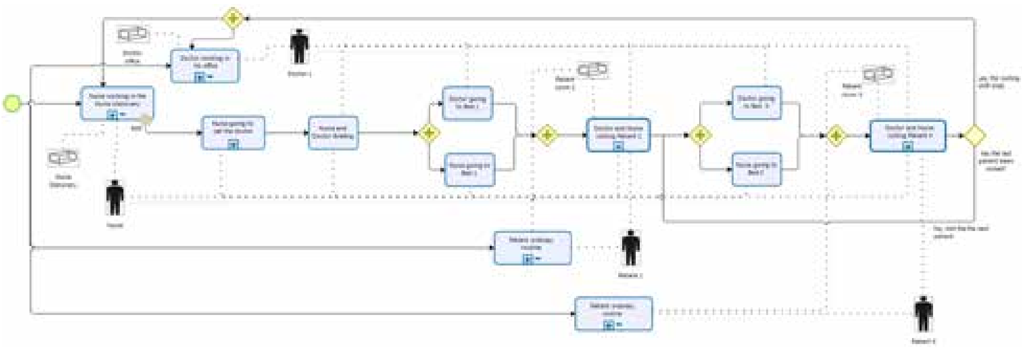

Figure 1
A building use process (in this case a visiting routine in a hospital ward) represented by means of BPMN approach. Actors and spaces entities are connected to the activities sequence, providing a formalization of What (which activity) is performed, Where and by Whom.

ecuted during the process;

- **Connectors**: links to connect an activity to another activity in order to define an operational sequence flow. Other classes of connectors allow to associate other kinds of entities to activities;
- **Events**: occurrences that "happen" during the process, starting, delaying, interrupting or ending a flow of activities;
- **Gateways**: modeling elements that control the pathways of the process, its diversions and its convergences, allowing parallel or exclusive paths.

For the purpose of our research, these classes of entities (with their subclasses) are relevant, but not sufficient. So, in order to make the BPMN system able to represent building use processes, we chose to rely on the ability to extend the BPMN representational approach by creating two new classes of artifacts:

- **Actors**: entities representing each actor involved in the building use process, in order to connect it to the performing of the activities he/she has to carry out;
- **Spaces**: entities representing the spaces of the built environment, and necessary in the BPMN environment in order to effectively connect the use process to the building, and allow its simulation in the 3D environment.

We consider the addition of spaces and actors entities to the process representation a key point of our modeling approach. The formalization of spaces effectively provides the conceptual connection between the building use process based on the organization's operational dynamics, and the building design solution provided by the architect. In this way, the activities, considered elementary units of the organization's operational workflow, are not abstract anymore, but explicitly represented in the building model, providing a representation of what is going to happen, where, and by whom. Although the BPMN representation already takes into account actors' declaration by means of "swimlanes" (White, 2006), we chose to develop a specific artifact for the actors, since in a building use process formalization each actor has to be associated to several activities and this is hard to represent with the swimlanes system (Figure1).

The BPMN approach allows us to represent not only complex sequences of activities, but also their articulation in (and relation to) time: specific time-triggers or event-triggers can represent conditions for an activity to be activated, interrupted or deactivated, influencing the performing of the building use scenario. Gateways are used to formalize and control parallel or exclusive executions of multiple activities; they can be considered decision points in the flow of activities, since they allow testing the model status for specific conditions and choosing which sequence of activities to perform. For instance, if we imagine a scenario where a doctor is visiting a series of patients (as the one shown

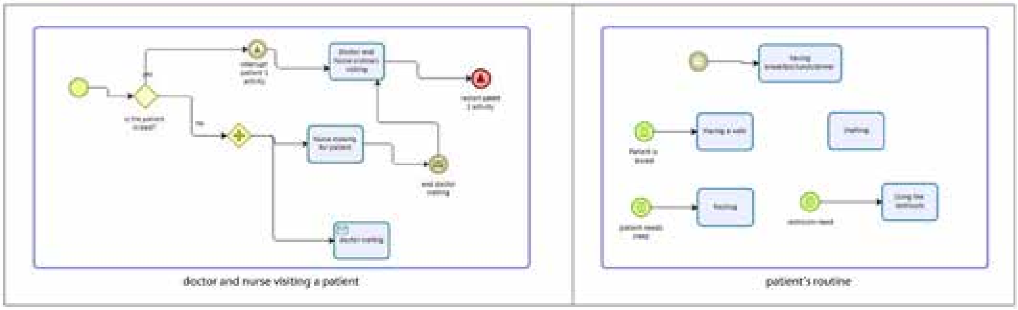

Figure 2
An encapsulated set of activities (on the left) and an ad-hoc process (on the right) used in the building use process representation. Their role is to make more manageable the representation of complex processes and not-structured activities.

in Figure 1), a gateway formalizes the necessity of checking the patient presence and, in case of his/her absence, it adapts the use scenario by directing the doctor to the next patient.

The BPMN ability to encapsulate activities in sub-processes also allows us to manage complex processes and to reuse the same activities structure several times. At the same time, non-structured or intermediate activities (such as "using the restrooms", or "having a walk") (Tabak, 2008), are represented by means of ad-hoc sub-processes that can be invoked during the actual simulation according to probabilistic curves (Figure 2).

In order to make the process representation more flexible and adaptable to different systems (meant as building + activities + users), we also used BPMN messages and signals to stop and restart different sub-processes depending on specific conditions or events. The BPMN system allows us to actually export (via XML) and execute the represented building use process in external simulation environments and to use it as input for such systems. For the development of the building use scenario in the BPMN environment, we chose to use Bizagi, a freeware business process modelling software [1].

SIMULATING BUILDING USE PROCESSES IN 3D VIRTUAL ENVIRONMENT

The BPMN approach is a valid way to represent and simulate processes composed of one or more flows of activities involving some actors. Nevertheless, the BPMN representational system alone is not sufficient to effectively represent a building use process. In fact, it is not able to take into account and consequently simulate how the use process (meant as a set of activities and actors involved) is influenced by the built environment, and how it will be actually be carried out in it. In order to provide architects and clients with a reliable prediction of how the building users carry out the defined activities, we chose to integrate the BPMN representation with a 3D simulation environment, where the formalized use process is effectively simulated within the built environment provided by the architect. In this environment (developed by means of the game engine Virtools [2]), the building use process, previously formalized in an abstract way in the BPMN system, is connected to the virtual model of the built environment where its activities are supposed to be performed.

To compute and simulate the use scenario developed in the BPMN model, a specific script has been developed in the Virtools game engine by means of behavioral blocks -visual programming blocks that correspond to the different activities represented by them. In Virtools' scripting environment, we chose to develop a specific programming level for the formalization and computation of the use scenario; its role being to guide and control the execution of the sequences of activities, adapting their performing to the environment and to the status of the users' involved. It also enables control and simulation of serendipitous events, triggered by the physical (actually, geometrical) proximity and location of the actors within the simulated built environment (Fig-

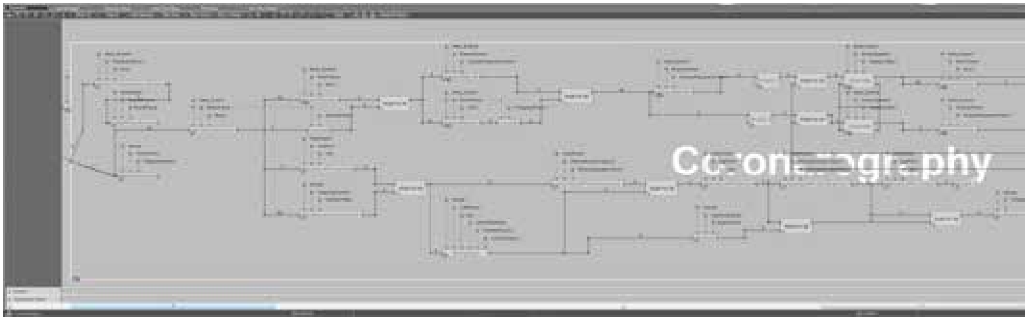

Figure 3
A part of the building use scenario script developed in the Virtools scripting environment.

ures 3 and 4). Such chance encounters may trigger different performance paths. In addition, we chose to equip activity entities with specific scripts to simulate their performing in order to coordinate actors' actions and cooperation. This is a fundamental difference from previous agent-based models, where the activities simulation is generated by the sum of autonomous actions and decisions of the users, with several limits in terms of manageability and coherence of the output.

To improve the adaptation of the scenario simulation to the built environment and its status, we chose to integrate the scenario script with some agent-based components, intended to control some autonomous aspects of virtual users' behavior (for instance, path decision, walking actions, obstacles avoidance, local interactions with other entities, such as doors or other agents). This choice has two main advantages: resemblance to the visual reality of the resulting simulated phenomenon, and improving the manageability of the computation system. The first consists of the possibility to reduce the rigidity of a process-driven simulation by including variations related to single actors' behaviors, actions and decisions. In that way, we can simulate serendipitous events generated by the interactions of

Figure 4
The simulation of the building use process in the 3D visualization environment of Virtools.

the agents with the built environment that are not predictable in the scenario development. The ability to provide actors with some degrees of autonomy allows us to represent some aspects of users' behavior that would be difficult and time-consuming to represent and compute at the process level. For instance, the abilities of a user to compute a path in the built environment and perform the movement actions can be easily developed and controlled directly in the agent entity, while their representation and computation at the process level would be very difficult, and if iterated for each agent and activity would make the process representation too complex and difficult to manage.

A CASE STUDY

Operational efficiency in hospitals is strongly influenced by the physical design of the built environment. Although hospitals are relatively complex buildings, their use-pattern is relatively straight-forward, which is advantageous for our research since it provides a comprehensive and agreed-upon data set against which the model can be tested. For this purpose, as a first implementation of this model, we chose to simulate the functioning of different hospital wards, in routine and in discrete emergency cases. The large quantity of money that is being invested in healthcare facilities suggests that enhancing, even by little, the efficiency of routine procedures might lead to substantial savings in time and costs.

As a first implementation of our approach we chose as target the cardiology department of the Bnei Zion medical center in Haifa, Israel. The size of the department and the complexity of the activities are appropriate to test our simulation model. We chose to observe and simulate both a routine procedure - a coronary catheterization - and a more complicated scenario, such as the intensive care unit, whose emergent phenomena are harder to predict.

Several coronarography events have been observed during a period of a week, after a series of meetings held with the principal physician, who explained to the observer the list of procedures performed during the operation. Reproducing the activities related to this operation in the BPNM environment and simulating it in the virtual environment was not a difficult task, because of the structured nature of the procedures involved in scheduled surgeries. Simulating the activities performed in the intensive care unit required extensive observations, long meetings with the medical staff, and still we were only able to reproduce them computationally within a high degree of abstraction. During the experiment, two different configurations of the physical environment provided by the architect have been tested in relation with the same use scenario, in order to support the design team and the hospital managers in the evaluation of their functional quality (Figure 5).

In order to validate the simulation output, some medical specialists have been interviewed to verify the validity of the formalized use process and the reliability of the simulation results. The use process model proposed in this paper proved to be highly reliable in situations when a clear sequence of observable activities can be recognized by lightly trained observers. When the inherent complexity of the situation produces phenomena hard to decompose in activity chunks, the model shows some limitations.

Future developments will involve exploring different way of decomposing inherently complex situations in sequence of chunks computationally manageable.

CONCLUSIONS

By integrating a building use process formalization with its visual simulation in a virtual environment, the proposed model offers architects and clients the opportunity to test the functionality of a design solution and to foresee its consequence on users' behaviour, before actually being constructed and occupied. The building use process simulation approach allows architects, clients and process planners to easily formalize a use scenario in terms of the activities performed, the actors involved and the spaces where such activities will take place. The visual/geometric simulation provides the necessary connection of the abstract scenario to its perform-

Figure 5
A screenshot from the simulation of one of the proposed configurations for the Cardiology department of the Bnei Zion Medical Center [3].

ing in a defined physical environment, thereby introducing the environmental constraints that affect the process and contribute the important element of serendipity. The 3D visualization of how such use process is effectively performed by future building users, is helpful in making the results accessible to the experts who must judge the outcomes of the simulation.

Differently from previous activity-based models where the use process is entirely computed before and then merely visualized, in the proposed model the use scenario is computed in real time during the simulation, providing a better adaptation of the sequence of activities to the built environment and its occupants and, consequently, a more coherent and reliable simulation output.

By providing a real time simulation of users' behavior within a defined physical environment, although limited to specific use cases and processes, this simulation model would support:

- Architects and clients in evaluating the functional performances of a design solution before it is actually built, leaving them the possibility to correct errors and solve critical points;
- Process planners, analysts and building managers in testing different workflows and operational procedures, and to test different configuration of human resources such as number of workers, their profile and specialization, their scheduling.

So far, the research shown in this paper has mainly focused on simulation of users' behavior in terms of activities performing and operational management. It would be interesting in follow-up research to introduce social and environmental psychology data in the simulation model, in order to provide a more comprehensive and reliable prediction of users' life and activities in buildings.

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Flexing Wind

Aerodynamic study of architectural windbreak

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Abstract. *The aims of the Flexing Wind project, investigated in an intensive cross-disciplinary course, were twofold. First was to learn about aerodynamic phenomena around buildings. Second was to explore ways to observe, measure, and control the negative effects of wind around specific pedestrian areas, tram stops, and public sites in Melbourne City. Using tools such as a weather station to collect data and CFD software to simulate aerodynamic phenomena students could study the wind conditions in one of the windiest areas in the Melbourne downtown. Various do-it-yourself tools such as mini wind tunnels, handheld probes and sensors were used to evaluate the performance of potential design options, which lead to prototyping full scale adaptive architectural windbreaks.*
Keywords. *Urban aerodynamics; windbreak; wind tunnel simulation; Computational Fluid Dynamics; architectural prototype.*

INTRODUCTION

A better understanding of urban aerodynamics will positively influence design decisions in architectural and urban projects. The wind flow and dispersion through a city determine environmental air quality, wind pressures on buildings, urban heat islands, pedestrian comfort, and ambient noise level in the surrounding environment (Boris, 2005; Zaki et al., 2010). However, only a few existing techniques have been developed to deal with the habitability and comfort issues due to strong wind conditions on pedestrian areas (Cochran, 2004). These are mainly done on the urban planning level or by introducing trees and shrubs as vernacular shelterbelts. Studies have been done on how aerodynamic characteristics of windbreaks can be used to resolve pedestrian comfort issues (Gandemer, 1981).

This project was conducted as an intensive three-week cross-disciplinary elective in the School of Architecture and Design, RMIT University, offered to architecture, landscape architecture, and engineering students. The outcomes of the explorations include:

- Wind maps of the sites (a major intersection located at the northern axis of Melbourne and the alleyway at the rear-entry of the RMIT University Design Hub building), derived from data captured using handheld probes and a weather station
- Analysis and evaluation of the performance of a series of windbreak options designed for

- each particular site performed using a small-scale wind tunnel test and Computational Fluid Dynamics simulation.
- Three prototypes as a system of mitigation for conflictive wind environments (deflector and diffuser devices). Two of these prototypes are reported in this paper.

The main task was to investigate the design and performance of architectural windbreaks as design interventions on the prevailing wind conditions (directions, pressure, speed) by controlling eddy areas around a building. Eddy is a turbulent wind condition caused by the changes of wind pressures [1]. The key outcomes were design prototypes of adaptive architectural windbreaks, which were installed on public footpaths. Feedbacks were gathered around issues such as the performance of the proposed windbreaks and the impact of installing the windbreak on the windy sites.

METHODOLOGY

The research and design aspects of the elective projects was conducted by a group of students (11 masters and undergraduate students) and highly guided by investigators (the teaching staff in the elective, authors of the paper). At the beginning, the students had access to a wide range of literature on the theory of windbreak design. Topics included studies about aerodynamics in urban contexts and wind comfort using Beaufort scale criteria where wind is considered as a function of speed and sensations felt (Gandemer, 1978); and systems to wind control such as windbreaks (Cochran. 2004). The students were also presented with introductory lectures on the technical aspects of the project by the teaching staff as well as an external industrial expert. During this stage the students learned about causes and effects of more common aerodynamic phenomena in cities produced by the wind flow interacting with buildings and affecting public areas.

In the second stage, students were introduced to the methodology and tools on windbreak design. The literature included the authors' earlier research projects, such as the parallel wind analysis method and the mini wind tunnel (Salim and Moya, 2012) and methods of designing kinetic façade prototypes (Sharaidin et al., 2012). Digital technologies such as Computational Fluid Dynamics (CFD) were also used to simulate the aerodynamics of the external environment. Additionally, using a mini wind tunnel, physical experiments such as erosion test (wind flow visualization using particles on a dark-coloured background) and smoke test (Salim and Moya, 2012) were applied to evaluate the different designs of the windbreak systems. Through these methodology and tools the students could run different experiments focused on the analysis of wind phenomena.

The proposed methodological experiments were divided into several tasks:

1. Build a system to quantify and visualise wind data (wind speed). The tools made available to the students were: a low-cost commercial weather station, scientific indoor condition measuring probes, low-cost electronic sensors and development platform (Arduino). Through a selection of the above tools, the students will develop a system to collect and visualise the data from the public space. The intention is to develop a wind map of the urban zone using instruments to measure the movement of wind.
2. Construct both a physical and digital module of the selected site. Conduct simulations to understand the effect of wind in an interactive fashion.
3. Design an artificial windbreak prototype for public space (passive or kinetic structures). Students were encouraged to test their design iteratively through both physical and digital simulations.
4. Build and install a full scale windbreak prototype. Students built a representative part of their design in a scale one by one. This prototype was installed in a windy site in the city to evaluate impact on public space and performance to mitigate wind problems.
5. Evaluate the wind mitigation achieve after of the prototype installation.

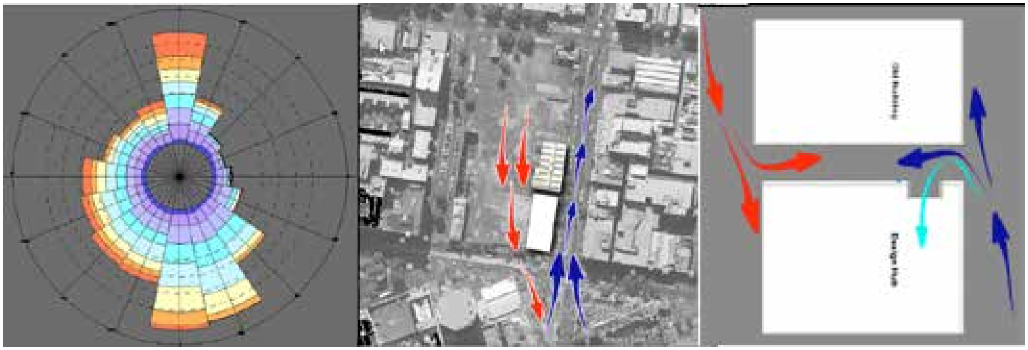

Figure 1
From the left to right: the wind rose from Vasari and wind map derived from the site observation.

PROJECTS: ANALYSIS, DESIGN AND OUTCOMES

The two main approaches to develop a wind control structure were the exploration of porous patterns as a wind filter and the concept of a shell as a wind deflector. The challenge was to not only design a structure to control the negative effect of wind detected in the site, but also produce low impacts in the surrounding space. This meant that the aesthetics is an important element alongside the functional aspect of the windbreak.

Milk.Crate.Break Project (by Tamara Cher, Xuan Son Nguyen, Romy Peterfreund)

The site for prototype 1 *Milk.Crate.Break* is at the rear entry of the RMIT Design Hub (Swanston Street entrance). It is a narrow alleyway close to an alcove with an operable door opening. Through a study of the historic data of the site it was found that there is a prevailing wind blowing through the site, direction alternating depending on the season (Figure 1). When the door is opened the sudden pressure difference produce a noticeable wind gust into the building.

The study of the site (Figure 1) was focused on the investigation of the differences of wind conditions between summer and winter seasons, as well as analysing the impact in this area.

The first finding of this study showed that wind has two predominant directions (north and south). This meant that wind passing through the passage leading to the entrance changes its direction throughout the year. The effect on the entrance is the same but the design of the windbreak should deal with both wind directions.

Using Vasari as CFD software it was possible to visualise how the gust of wind had a curved movement producing two separation zones with low pressure areas. One of these areas coincided with the entrance of the building, producing an input of wind when the gate was opened. These simulations were validated with measurements of the wind speed using the anemometer on the low-cost weather station. On the day of data collection it was found that the wind coming closed to the façade had an average speed of 3.7m/s at 2m height, but this velocity increased up to 4.4m/s when was blowing through the passage (Figure 2).

The first approach was to use a shell or canopy to deflect the wind to maintain the low pressure area in front of the entrance. Later the design process progressed to the design of a skin with some kind of porosity to control the wind speed. This porosity concept evolved from a surface with simple patterns of holes to different patterns with a variable density of porosity (Figure 3), following the indications of the studies by Gandemer (1981) on windbreaks.

As part of the project the students were required to construct a section of their design in full size and install it on site. The *Milk.Crate.Break* team decided on the front section of the design to be constructed

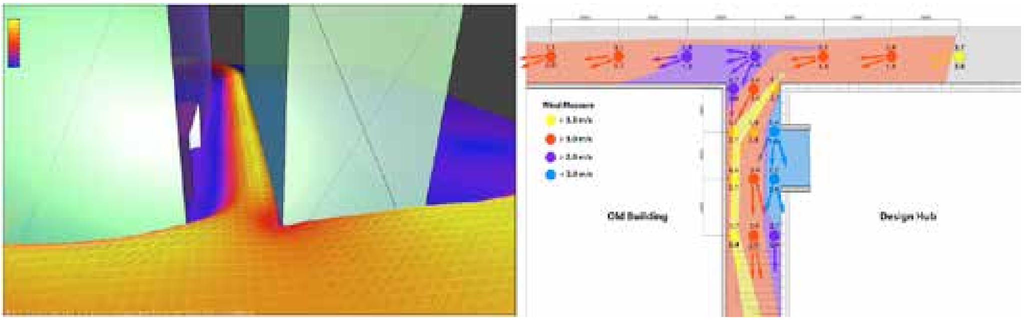

Figure 2
From the left to right: CFD visualisation and windmap of the site done in Vasari.

at the full scale. This had the implication that a new structural system is required for the design. Through further exploration the students decided on using milk crates as the main building material, factors influenced their decisions included: structural (modular self-supporting, easy to assemble and disassemble), sourcing (free and readily available), a cultural significance (Melbourne's laneway). The inherent structure and porosity of the milk crates also offered the students additional design possibilities: The design was adapted to take advantage of the crate volume to produce a design with a double skin. The students explored several options of patterns for an adaptable second skin through CFD analysis. The first option had a pattern of Venturi funnels working as a diffuser to decrease the wind speed in the outcome side of the wall. The second version was a pattern of triangular petals with a more simple system of petals aperture for the density control. The final design was a pattern of triangle flaps based on the shark skin. This was the options chosen because the parallel triangular surfaces deflected the wind more efficiently to produce an upward air through the wall. The experiments compared these different patterns with 20%, 40% and 60% of porosity. For each case, the pattern moves depending on the pressure of the wind, where used to deflect the wind upwards as well as absorbs a fraction of the wind energy (Figure 4 and 5).

The final concept was a structure with a double layer of porous skin. The first porosity layer was a regular graph design which ameliorated the wind speed. The second shark-skin pattern layer reduced the wind flow close to zero. Between both layers, the internal chamber in the structure was designed to deflect the wind vertically. In this way the pressure on the structure was reduced to maintain the structural stability.

The students' final design was a windbreak that spans the full width of the alleyway, 2.5 meters in height, offering protection for a large area in the proximity of the door. The design form is symmetrical to work with both wind directions. There is one opening at each end to allow access through the

Figure 3
From the left to right: the first version of shell, the second version of a porous shell, the study of porosity density.

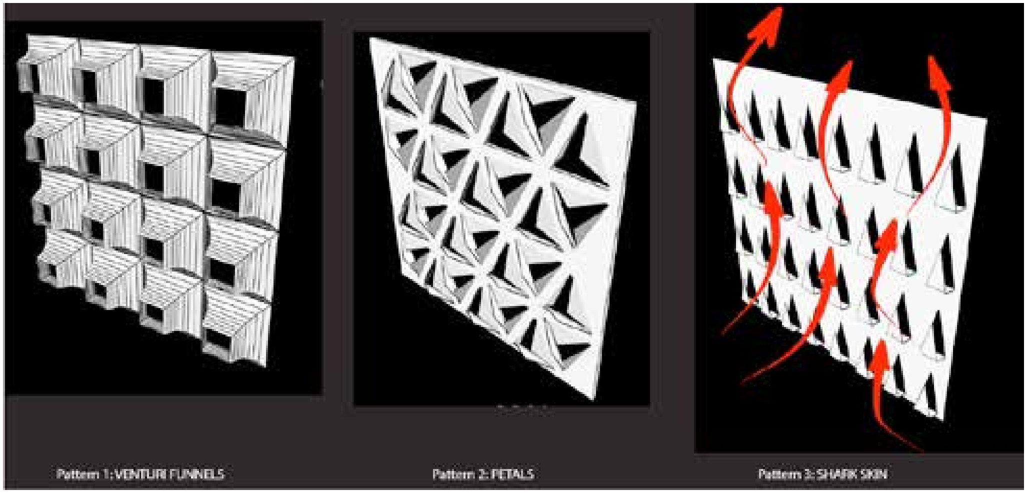

Figure 4
From the left to right: Venturi funnels, petals and shark skin.

site and into the building. The porosity system is designed for the surface of the windbreak, with lower density at the lower part the design to offer more protection (Figure 6).

Further testing (both simulation and in the physical mini wind tunnel) were conducted to confirm the functionality of the adapted design. Measurements were taken to evaluate the design.

Lyrebird Project (by Mikhail Kochev, Sara Metanios, Daisy Leung, Rico Shuyuan Zhang)

The site of prototype 2 *Lyrebird* is located close to a street level entrance to RMIT University Building 14 (Swanston Street). The onsite data measurements revealed a predominant wind direction from the south to north. The students noticed a strong and

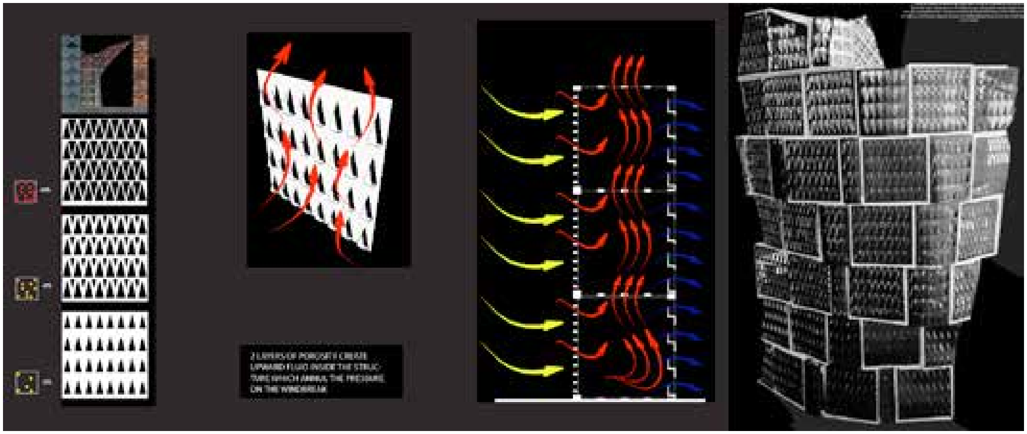

Figure 5
From the left to right: porosity variations and effect of wind passing through the structure, final installation.

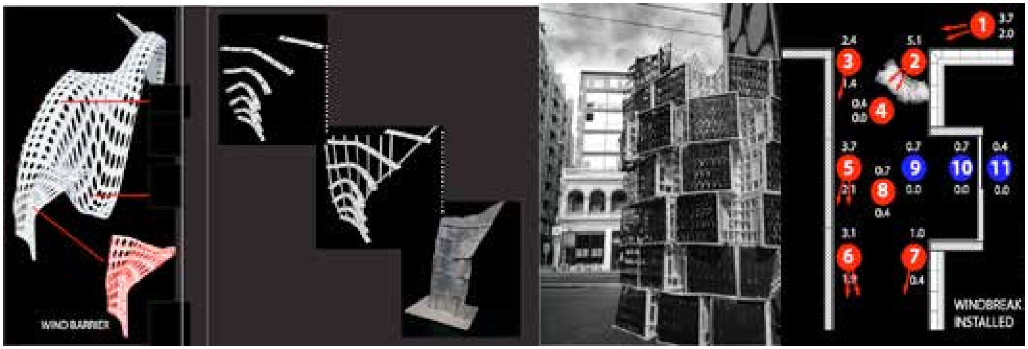

Figure 6
From the left to right: design process from the concept to the installation and measurements in the site.

turbulent wind close to the building facades side of the pedestrian sidewalk. Although a number of trees are present on the street near the site, it was evident that the wind conditions were not improved for pedestrians. Erosion test of the site model was conducted in the mini wind tunnel to reproduce the more relevant phenomena. The phenomena observed were: the wind blowing along the street, the wind effect around the corner on the building, and the effect that could be produced by placing structures over the entrance (Figure 7). These simulations demonstrated a channel effect occurring in this area with a high level of turbulence from the friction with the buildings' walls. This was identified as an issue for the building entrances and other points around the pedestrian circulation routes. The design objective was to protect the street level entrance from the prevailing and local wind conditions.

The student drew their design inspiration from bird feathers, in particular the fan-like tail of the Australian Lyrebird. The idea was to mimic the natural curvature of the feather to form a curved shell for the entrance (Figure 8). Design iteration of the form and dimension of the windbreak was mainly conducted through physical wind tunnel tests and CFD experiments. These digital tests were focused to find the more efficient curvature for this roof to deflect the wind. This exploration found that a double curvature performed a very good protection rather a single curve (Figure 9).

In the wind tunnel test, a simple curved canopy shows a good performance to deflect the wind without significant loan on the structure: the arched shape was able to deflect and guide the wind over the building opening. This final version was chosen as the structure shown to be a more effective windbreak. These tests demonstrated that the structure does not produce lateral strong gusts and the protection area was large enough to provide shelter against strong winds around the entrance of the

Figure 7
From the left to right: mini wind tunnel and erosion test of the proposed windbreak design, wind map of the site.

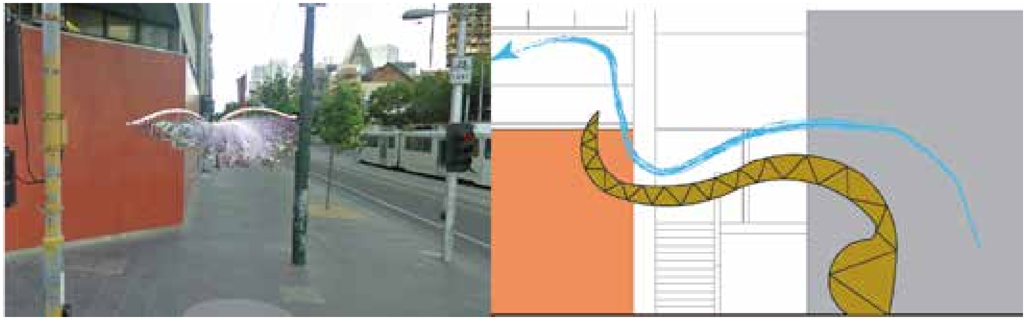

Figure 8
From the left to right: concept based on tail of the Australian Lyrebird and hypothesis of wind deflection.

building (Figure 10).

Detailed porosity exploration was also carried out using smoke test to study the best sequence of gaps and thickness of the barrier with different wind velocities (Figure 11).

The final design was a frame and infill system with triangular "slot-in" panels on vertical structural frames. Each triangular panel contains a movable flap with functions similar to prototype 1. As these panels are more visually prominent compare with prototype 1, the students worked to adapted them as a visual wind indicator to increase public interaction with the windbreak. This was done through installing an Arduino controlled LED display, where the display was driving by wind data from an electronic sensor (anemometer). This was not installed

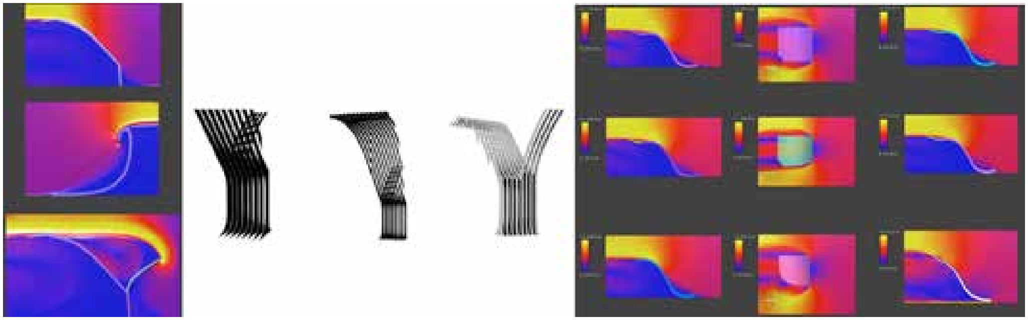

Figure 9
From the left to right: CFD tests for different curvatures, first project design and wind test of curve profiles.

Figure 10
From the left to right: CFD test and wind tunnel test for the final design.

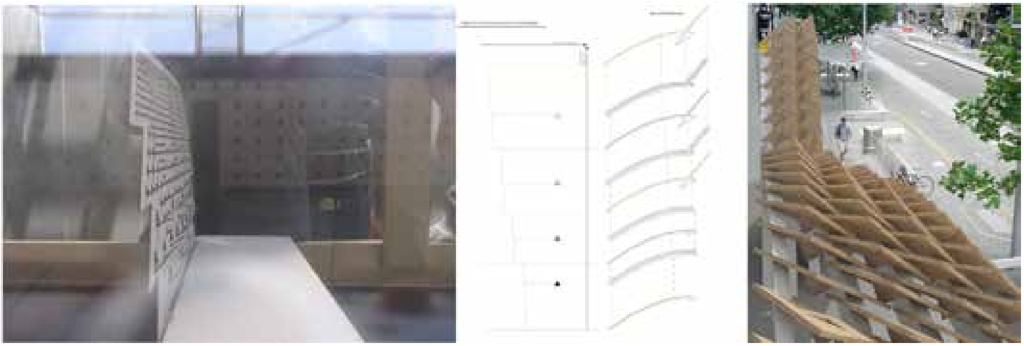

Figure 11
From the left to right: smoke test, axonometric of panels and final render.

on the final installation due to time constraints. Many factors such as site permit restriction and fabrication constraints dictated that only approximately 2 meters by 2 meters by 2 meters of the design was constructed and evaluated on site. The students applied bright paint to observe how colours have a relevance to intensify the visual aesthetic of the structure in the public area (Figure 12).

GENERAL EVALUATION

One positive outcome of this academic project was the opportunity to share knowledge from different fields that conduct work on the city and its current problems. The use of technology helps us to understand the dynamic phenomena like wind in cities, through collecting data (both in the physical and virtual realm, on site and through simulations) and make sense of that information. This was the intention of this project: to teach students to work with methods and technological tools to study complex phenomena.

This first part of the objective was fully complete for the students. In the short three weeks, through the study of the literature available in the field of wind engineering and the tools such as Vasari CFD and a low-tech mini wind tunnel, the students were able to gain a good understanding of the basic aerodynamic effects to begin their own design exploration in this field. The potential of these tools for pedagogic purposes was evident. The visual interactive feedback helped the students to gasp with the comprehension of these complex phenomena, and as a platform for discussion the design performance. The visual documentation of the design testing process (both still images and videos) formed a large part of the presentation material for the students

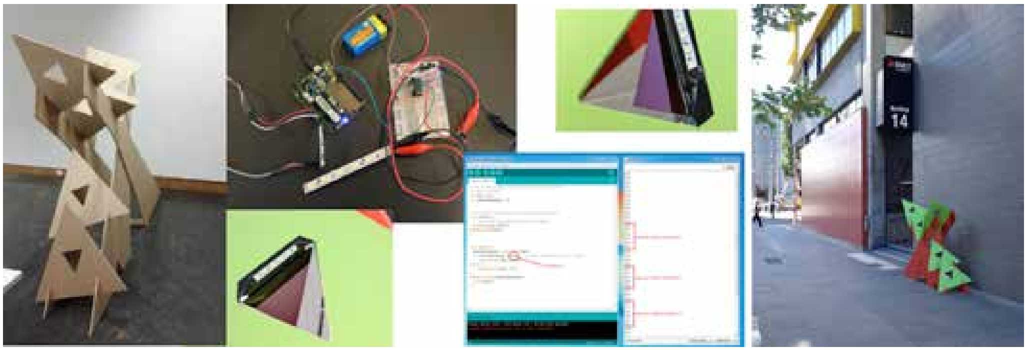

Figure 12
From the left to right: prototype, Arduino platform and installation.

to communicate their design intent to the teaching staff and invited critiques.

The ready-to-go low-cost commercially available weather station, with its simple interface, was quick to be adapted by the students to be used for site analysis and to prototype performance evaluation tool.

Arduino Platform and electronic sensors have proven to require a learning curve too steep for most of the students to be able to utilise them in their design. The Arduino and sensors induction were provided as part of the course material, but whether to incorporate it within the design was a choice left for the individual student team. All of the students welcomed the half day hands-on session exploring Arduino sensors and motors. The students were guided through a series of selected examples that introduced the concept of Arduino microcontroller and a collection of electronics. With each example its possible application to the windbreak design was discussed. Following the demonstration, a proportion of students actively sought additional equipment and assistance to experiment it further. This demonstrated that new technology was easily taken up students when it is presented as a useful resource to extend the possibilities for their design proposal.

Apart of the design aspect of the windbreak, the challenge of a built prototype was a very positive learning process because students were encouraged to deal with physical problems and technical solutions. Even if the prototype was not a fully functional model, many issues concerning scale, materials, and cost were considered and evaluated for each project. This dialog of material and constructability also opened up new design exploration. Take the intention of the *Milk.Crate.Break* project to use recycle plastic boxes as an interesting example. The decision to use milk crates as a building material led the team to explore the features of a double-layer windbreak. This project studied the performance of different porous patterns when a simple plastic mesh may be functionally sufficient. This demonstrated that performance and constructability should inform each other in design.

The task of constructing a physical prototype and installing it on site helped students to understand how an urban intervention can also have a visual impact in the space. For instance, the colour in the structure of *Lyrebird* project was considered as a parameter of communication. Additionally, the project also considered to use an anemometer driven LED display which could be activated with the wind, sending a live visual signal to the passers-by when the wind speed increases over the comfortable levels. Thus, the performative aesthetics of a windbreak as an urban element can also have a functional aspect that informs people of the surrounding environmental conditions.

CONCLUSION

Wind around buildings and in public spaces can produce negative effects that are necessary to mitigate. This paper reports on a design-construct cycle of a site specific architectural windbreak, conducted in the form of a design studio taken place over an intensive three-week period at the RMIT University, Melbourne Australia. After a detailed study of the site, the students successfully incorporated aerodynamic theory into their design thinking and demonstrated the use of CFD simulation tools and physical wind testing to assist their design process. The impact of the windbreak on the site was quantitatively measured and evaluated. This is done by assimilating the studies of local wind conditions and vernacular systems and testing the design in wind tunnel simulations.

The results and prototype designs are preliminary, however they demonstrated the possibilities of designing windbreaks that have aesthetics features as well as the functional capacities to provide comfortable pedestrian areas.

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Real-time Environmental Feedback at the Early Design Stages

Creating a conceptual analysis tool by teaching artificial neural networks with design inputs and monitored energy consumption data

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Abstract. *It has been argued that traditional building simulation methods can be a slow process, which often fails to integrate into the decision making process of non-technical designers, such as architects, at the early design stages. Furthermore, studies have shown that predicted energy consumption of buildings during design is often lower than monitored energy consumption during operation.*
In view of this, this paper outlines research to create a user friendly design tool that predicts energy consumption in real-time as early design and briefing parameters are altered interactively. As a test case, the research focuses on school design in England. Artificial neural networks (ANNs) were trained to predict the energy consumption of school designs by linking actual heating and electrical energy consumption data from the existing building stock to a range of design and briefing parameters.
Keywords. *Environmental design tool; energy prediction; artificial neural networks; building operational performance; schools.*

INTRODUCTION

There are many environmental 'design aids' available, with the objective of helping designers make sustainable design decisions. These design aids can largely be grouped into the following categories (Morbitzer, 2003):

- Design guidelines / rules of thumb
- Steady state calculation methods
- Correlation based methods
- Physical modelling
- Building simulation

Given that environmental design problems tend to be 'wicked' (Rittel and Webber, 1973), and thus distinctly novel and unique, rules of thumb, basic calculations and correlation methods are often inadequate techniques (Morbitzer, 2003; Pratt and Bosworth, 2011) and physical modelling has the disadvantage of being very costly (Morbitzer, 2003). When used correctly, the most powerful design aid available for the analysis of environmental performance is building simulation (Morbitzer, 2003). Building simulation is, however, rarely used by architects at the early design stages (Pratt and Bosworth, 2011).

Architect and psychologist Lawson (2004; 2006) states that simulation tools are not 'design' tools but 'evaluation' tools which are used to assess designs after they have been designed. A major barrier is the time taken to input all the required information, such that the designer can only afford to do it after the major design decisions have been made (Lawson, 2004). Also, the design space is constrained by the fact that commonly used building simulation tools produce static design proposals - it is therefore difficult, given time and economic constraints, to produce a wide range of design options (Pratt and Bosworth, 2011). In this way, the design space is sparingly populated because the models are discrete rather than continuous, thus omitting 'in- between' solutions (Pratt and Bosworth, 2011).

Furthermore, research, such as that carried out by CarbonBuzz [1], highlight the fact that the actual energy consumption of buildings regularly exceeds the design estimates, often by more than double.

Real world problems have complex and nonlinear interactions, therefore system behavior is often best learned through observations rather than modelling (Samarasinghe, 2007). In view of this, an alternative approach at predicting energy consumption in buildings is to collect large amounts of actual energy and design data and analyse the patterns between the two. One such source of actual 'observed' energy data in the UK are Display Energy Certificates (DECs) (CIBSE, 2009). One method of learning the relationships between energy consumption and design inputs are artificial neural networks (ANNs). ANNs are machine learning techniques inspired by the structure and processes of biological neural networks that take place within the brain (Haykin, 1999). ANNs were found to be suitable for assessing determinants of energy use in higher education buildings in London, UK (Hawkins et al., 2012).

In light of the above, two questions emerge:

1. Can an ANN based method for a design tool be developed that offers non-technical users the ability to predict energy consumption in real-time as they explore the design space?
2. Can such a tool be based on actual energy consumption, rather than simulated data, in an accurate manner?

As a test case, the research focuses on school design in England. The purpose of this paper is firstly to summarise the data collection process and describe the ANN method. Finally, the tool user interface development and preliminary results will be presented.

DATA COLLECTION

The data collection process was a desktop study with the aim of collecting as much design and briefing data as is freely available on hundreds of schools across England. Table 1 and Table 2 outline the input and output parameters for the ANN models. The energy data used to train the ANNs were sourced from the Display Energy Certificate (DEC) database, which are stored in the non-domestic energy performance register maintained by Landmark [2]. The annual electricity and heating fuel use (kWh/m^2/annum) figures were used as the output in this study. The following criteria were used to select the school buildings for analysis, ensuring the buildings are comparable with each other:

- The school has a valid DEC
- The school has one main building
- Age of construction and material use are consistent

Data on 465 schools have thus far been collected.

In addition to energy consumption, other data collected from the DEC database were total useful floor area (m^2) and building environmental conditioning type. The number of pupils in each school was gathered from the Department for Education's (UK) EduBase public portal [3] and heating and cooling degree days were acquired from the Central Information Point [4]. The geometric and site data were gathered by measurement or visual inspec-

Table 1
ANN inputs.

Input Parameter	Input Neuron Type	Data Range / Activation Criteria	Description
Construction Year	Continuous	1860-2010	Year the school was built
Phase of Education	Binary	(-1) Primary/elementary, (1) secondary/high school	Primary schools or secondary schools/sixth form colleges
Number of Pupils	Continuous	44-2013	Part-time pupils divided by 2, plus the number of full-time pupils
Internal Environmental Conditioning	Categorical	(-1) Nat. vent, (0) mixed mode, (1) mech. vent	Primary internal environmental conditioning strategy
Site Exposure	Categorical	(-1) Exposed, (0) semi-sheltered, (1) sheltered	'Exposed': no obstructions present (4 x the height of the school away); 'semi-exposed': obsts. lower than the school; 'sheltered': obsts. taller than the school.
Orientation	Continuous	-45° - +45°	Angle at which the external walls differ from absolute north, south, east and west. Positive angle for clockwise orientations.
North Façade Adjacency	Binary	(-1) Open, (1) obstructed	Obstructed if a building or tree is within 1 x the height of the building from the majority of the façade orientation
South Façade Adjacency	Binary	(-1) Open, (1) obstructed	See North Façade Adjacency
East Façade Adjacency	Binary	(-1) Open, (1) obstructed	See North Façade Adjacency
West Façade Adjacency	Binary	(-1) Open, (1) obstructed	See North Façade Adjacency
Floor Area	Continuous	$861m^2$-$15396m^2$	Total usable floor area
Building Depth Ratio	Continuous	2.50-16.60	Building volume / exposed external wall area
Compactness Ratio	Continuous	1.01-4.59	Perimeter of the building footprint / perimeter of a circle with the same area as the building footprint
Surface Exposure Ratio	Continuous	1.71-5.67	Building volume / exposed surface area
North Glazing Ratio	Continuous	0.00-0.13	Glazed area on the north façade / total floor area
South Glazing Ratio	Continuous	0.00-0.15	Glazed area on the south façade / total floor area
East Glazing Ratio	Continuous	0.00-0.11	Glazed area on the east façade / total floor area
West Glazing Ratio	Continuous	0.00-0.14	Glazed area on the west façade / total floor area

Input Parameter	Input Neuron Type	Data Range / Activation Criteria	Description
Glazing Type	Binary	(-1) Single, (1) double	Single or double/secondary glazing
Roof Shape	Binary	(-1) Pitched, (1) flat	Pitched or flat roof
Roof Glazing	Binary	(-1) None, (1) glazing	Existence of any roof glazing
Heating Degree Days	Continuous	1635.6-2843.3	Heating degree days during the DEC monitoring period
Cooling Degree Days	Continuous	73.9.7-425.2	Cooling degree days during the DEC monitoring period

Table 1 continued ANN inputs.

Output	Output Neuron Type	Data Range	Description
Heating Energy Consumption	Continuous	7-272kWh/m^2/annum	Annual heating fuel use
Electricity Energy Consumption	Continuous	7-95kWh/m^2/annum	Annual electricity fuel use

Table 2 ANN outputs.

tion from the online map software Digimap [5], Bing Maps [6] and Google Earth [7].

The building height was derived by multiplying the average number of storeys by 3.62m - the average floor-floor height of schools in the UK (Steadman et al., 2000). The building volume was then derived by multiplying the building height with the building footprint area, measured from Digimap [5]. Glazing percentages were measured from Bing Map [6] images using bespoke code developed in the Processing programming environment [8].

The construction year of the buildings were collected from each school's website where available otherwise they were derived from historical digital map software [5]. Data on schools of varying ages were collected to increase the size of the database, giving the neural network more data to learn from. A proportion of the differences in, for example, fabric quality and building systems between newer schools and older schools are likely to be picked up in the construction year neuron. Therefore, this neuron will exist within the trained network in the final design tool but fixed to the most recent date.

ANN ARCHITECTURE

All ANNs were constructed in Matlab [9]. The aim of the ANN method is to predict the energy consumption outputs (Table 2) based on a set of inputs (Table 1). A multilayer perceptron network was used for the study - Figure 1 shows the conceptual structure of this ANN. The hidden layer enables the system to generate nonlinear and complex relationships by intervening between the input and output neurons (Haykin, 1999). Each neuron in the input and output layer took continuous, categorical or binary values as outlined in Table 1 and Table 2. Prior to the training of the network, all continuous inputs were normalised to values between -1 and 1 to generalise the calculation process. Two ANN models were constructed, one with heating energy consumption as an output and one with electrical energy consumption as an output - both ANN models included all of the input parameters (Table 1).

A Levenberg-Marquardt backpropagation supervised training technique was used to train the feedforward network to recognise the patterns that exist in the dataset. The prediction performance of the ANN was assessed by validating the ANN with 10% of the gathered database on which the ANN had not been trained - the testing dataset. 10% of the gathered database was used to stop the training process before overlearning occurred (Demuth et al., 2008) and the remaining 80% of the database was used to train the network. The number of neu-

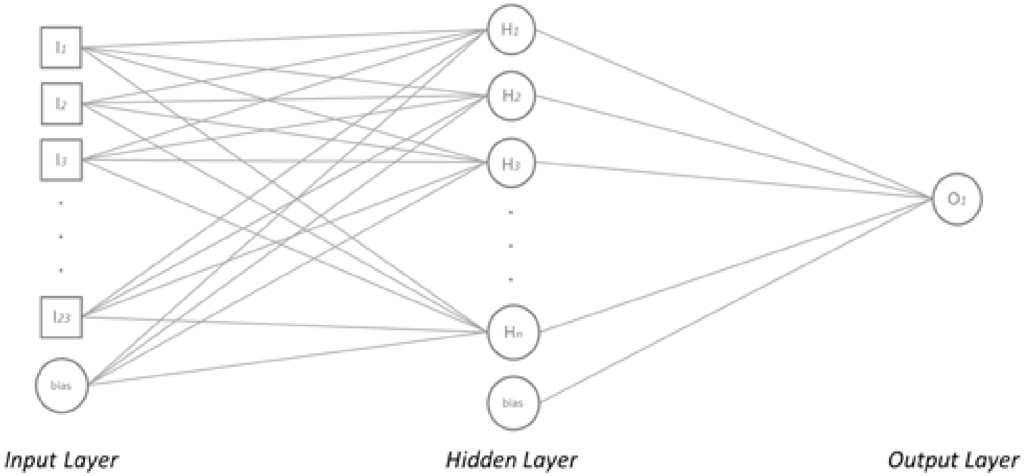


Figure 1
Conceptual Structure of the ANN.

rons in the hidden layer were altered between 2, 4, 8, 16 and 32 neurons. Each network configuration was trained five hundred times and the ANN with the lowest mean squared error (1) was selected for further analysis. Further analysis consisted of calculating the coefficient of determination (R^2) and the below performance indicators, (2) and (3):

Mean squared error (MSE) = $\sum_i^n \frac{(\hat{Y}_i - Y_i)^2}{n}$ (same units as output) (1)

Root-mean squared error (RMSE) = $\sqrt{\frac{\sum_i^n (\hat{Y}_i - Y_i)^2}{n}}$ (same unit as output) (2)

Mean absolute percentage error (MAPE) = $\frac{\sum_i^n \frac{|\hat{Y}_i - Y_i|}{Y_i}}{n}$ (%) (3)

Where Y_i and $\hat{Y}_i$ are the target and predicted outputs respectively for the training, testing or stopping configuration *i* and *n* is the total number of configurations in the training, testing or stopping datasets.

USER INTERFACE

Figure 2 shows a representation of the tool user interface. The tool is currently being developed in the Processing programming environment [8]. The ANN algorithms are integrated into this environment with MATLAB Builder JA [10].

The tool allows the user to sketch the footprint of the building by clicking and dropping vertices in an input window - these vertices can later be dragged or deleted. All other inputs are entered via sliders (continuous inputs) and tick boxes (categorical/binary inputs) thereby encouraging the user to 'play' and test different options, encouraging exploration of 'in-between' solutions in the design space. The ability to gain feedback in real-time results in the user being able to 'animate' the results and learn the relationships between the design inputs and energy outputs by the acceleration of change in the results as the design space is explored.

RESULTS AND DISCUSSION

ANN configurations with two and eight neurons in the hidden layer were found to produce the least prediction errors for heating and electricity energy consumption respectively. Table 3 summarise the results of the errors for the best performing ANN configurations. The electricity output was predicted with a mean absolute percentage error (MAPE) of 19.3%, while the heating output was predicted with a MAPE of 20.5%. These errors are an improvement

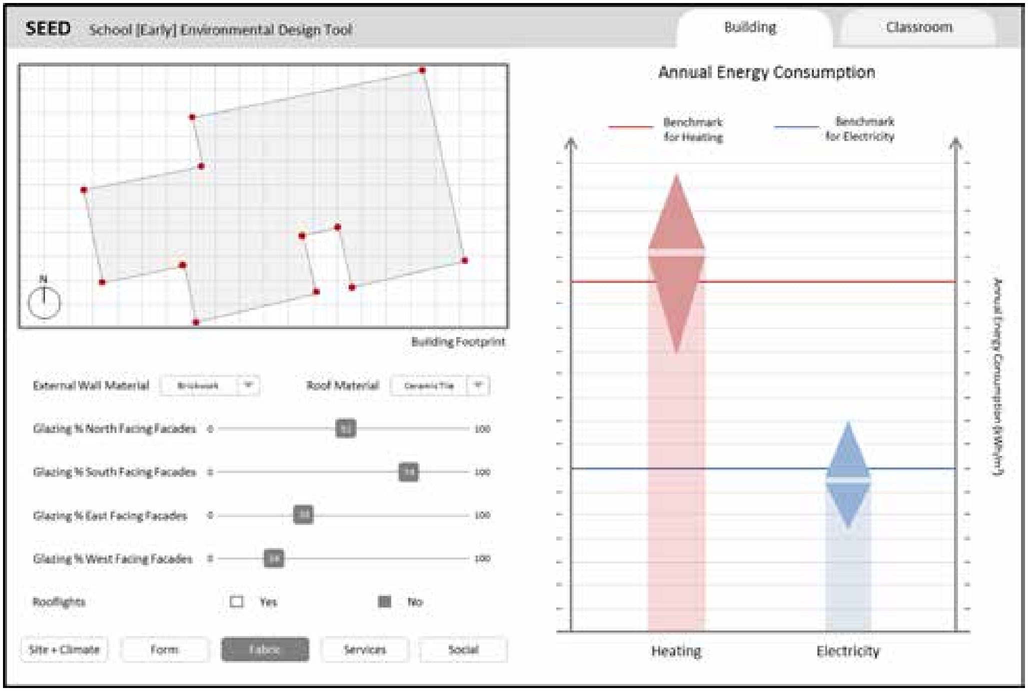


Figure 2
Representation of the user interface.

of 10.0% and 6.7% for heating and electricity energy consumption respectively, when compared to using the Chartered Institution of Building Services Engineers (CIBSE) Technical Memorandum 46 (TM46) Energy Benchmarks as energy performance indicators (Table 4). As mentioned in the introduction, Hawkins et al. (2012) used an ANN method to assess the energy determinants in higher education buildings in London, UK. The ANN method by Hawkins et al. produced MAPEs of 25.1% and 34.8% for heating and electricity fuel use respectively - the results from the research in this paper better these errors by 4.6% and 15.5% for heating and electricity respectively.

Figure 3 show scatter plots of the ANN predictions vs actual annual heating and electricity energy consumption from the testing dataset. The coefficient of determination (R^2) shows that the 23 design and briefing parameters (ANN inputs) explain 39% and 41% of the variation in annual heating and electricity energy consumption of the schools respectively.

From this initial study it appears that the ANN

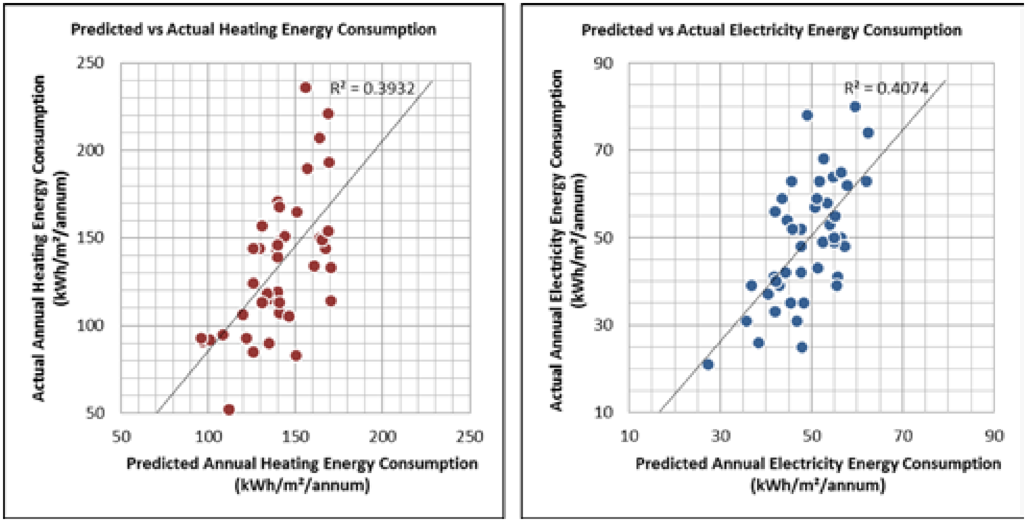
Table 3
Prediction errors of the ANNs - calculated from the ANN testing dataset.

ANN Output	RMSE (kWh/m²/annum)	MAPE (%)
Heating Energy Consumption	30.5	20.5
Electricity Energy Consumption	10.8	19.3

Table 4
Prediction errors of the CIBSE TM46 Benchmarks - calculated from the ANN testing dataset.

TM46 Benchmark	RMSE (kWh/m²/annum)	MAPE (%)
Heating Energy Consumption	41.3	30.5
Electricity Energy Consumption	16.7	26.0

Figure 3
Scatter plots of predicted ANN vs actual heating (left) and electricity (right) energy consumption.



method is viable for predicting energy consumption in existing school buildings. Nevertheless, further research is planned to improve the performance of this method and ensure it is viable for new school designs as outlined in the further work section.

CONCLUSION

This paper outlines research to create a user friendly design tool that predicts energy consumption in real-time as early design and briefing parameters are altered interactively. As a test case, the research focused on school design in England. Artificial neural networks (ANNs) were trained to predict the energy consumption of school designs by linking actual heating and electrical energy consumption data from the existing building stock to a range of design and briefing parameters. The initial design of the user interface was introduced in this paper.

For the energy consumption predictions, the ANN mean absolute percentage error (MAPE) was 20.5% for heating and 19.3% for electricity. The coefficient of determination (R^2) was 39% and 41% for heating and electricity energy consumption respectively. The aforementioned errors were compared with another method and study and produced lower errors, as outlined in the previous section. Nevertheless, it is desirable to reduce these errors further and improve the R^2 values. In order to improve both the performance of the ANN method and increase the relevance of the tool, further design inputs are likely to be required. The nature of this desktop study was to collect as many design and briefing inputs as are freely available. Acquiring further inputs, such as building services and fabric data, may require direct communication with individual schools or local authorities. This process is likely to be time consuming however is being pursued. Further actions to improve the ANN performance, as well as ensuring the tool is relevant to the design process and applicable to new school designs, are outlined in the following section.

It should be noted that the development of this tool does not have the objective of replacing traditional building simulation - instead it aims to act as a user friendly sanity check for non-technical designers, such as architects, at the early design stages.

FURTHER WORK

There are a number of developments underway in order to make the method of prediction in this research more accurate and the use of the design tool more relevant. These developments include collecting data on more schools across England; the pursuit of additional input parameters, as mentioned in the previous section; refining the input parameters for heating and electricity energy predictions separately; and the exploration of alternative ANN architectures. The final tool will go through a validation process using a number of new schools as case studies to ensure the method is applicable to new school designs. Finally, as the user interface develops, it will be tested by focus groups within industry.

ACKNOWLEDGEMENTS

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DesignScript: Scalable Tools for Design Computation

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Abstract. *Design computation based on data flow graph diagramming is a well-established technique. The intention of DesignScript is to recognise this type of data flow modeling as a form of 'associative' programming and to combine this with the more conventional 'imperative' form of programming into a single unified computational design application. The use of this application is intended to range from very simple graph based exploratory 'proto-programming' as used by novice end-user programmers to multi-disciplinary design optimisation as used by more experienced computational designers.*
Keywords. *Graph; scripting; associative; imperative.*

INTRODUCTION

The development of DesignScript is intended to be a response to the following trends in contemporary design practice (Figure 1). These trends can be described in terms of the following dimensions.

Scalable to different Computational skills

It is generally recognised that there are advantages in making design computation more accessible to a wider audience of designers. As software developers, we can interpret this not just as the need to make computational design tools easier to use by non-experts. In addition, there is an assumption or indeed an expectation that once designers have successfully accomplished some initial tasks, they will be interested in progressing from an exploratory approach to more formal programming methods. Therefore, we need to step back from the immediate requirement (to make computational design tools more accessible) and consider a more general requirement which is to support a progression in the development of

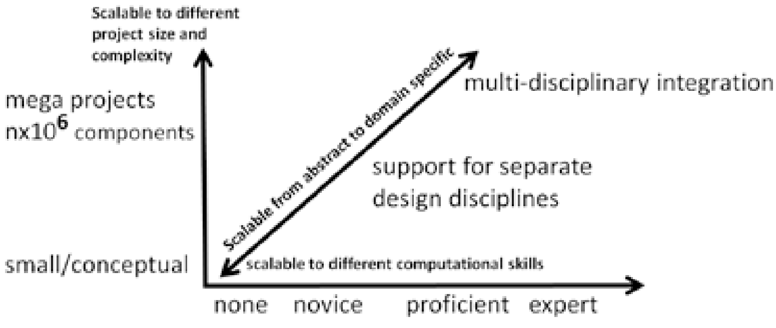

Figure 1
The three dimensions describing critical aspects of contemporary design practice.

computational skills, from 'no skills' to novice skills and hence to more proficient and expert skills.

This idea of a 'progression in computational skills' is based on the generally recognised critique of graph diagramming methods. While graph diagramming is an extremely powerful technique to enable novice programmers to create their first computational models with the minimum of experience and skill, it is generally recognised that the graph node representation does not scale to more complex logic. Indeed the visual complexity of the graph may become overwhelming and counter productive. It is exactly at this point where the application should encourage the novice programmer to make the transition from graph node diagramming to scripting: literally from 'node to code' (Figures 2-4).

Initially such scripts will reflect the graph node style of exploratory programing but as the designer continues to enhance and extend these scripts, the applications should help him to progress to a more formal style of software engineering by providing such facilities as a 'type' system and tools to support the refactoring of scripts into functions and classes.

An interesting by-product of a design application that supports different levels of skills is that it can encourage a more effective collaboration between team members with different skill levels.

Scalable from abstract to domain specific, including the support for multi-disciplinary design integration

While much of existing design practice is based on different disciplines (architecture, structural engineering and environmental performance, etc.) there are generally recognised advantages if a more holistic approach is adopted that integrates different ways of design thinking. This approach to design is often exercised through the formation of multidisciplinary design teams and can be encouraged by software that combines multiple analytical and simulation methods (Figure 5).

Another characteristic of innovative architecture practice is a 'return to first principles' often demonstrated through architectural form or engineering innovation. Often these principles may not have been previously associated with architecture or supported by existing design applications. This suggests a two way progression:

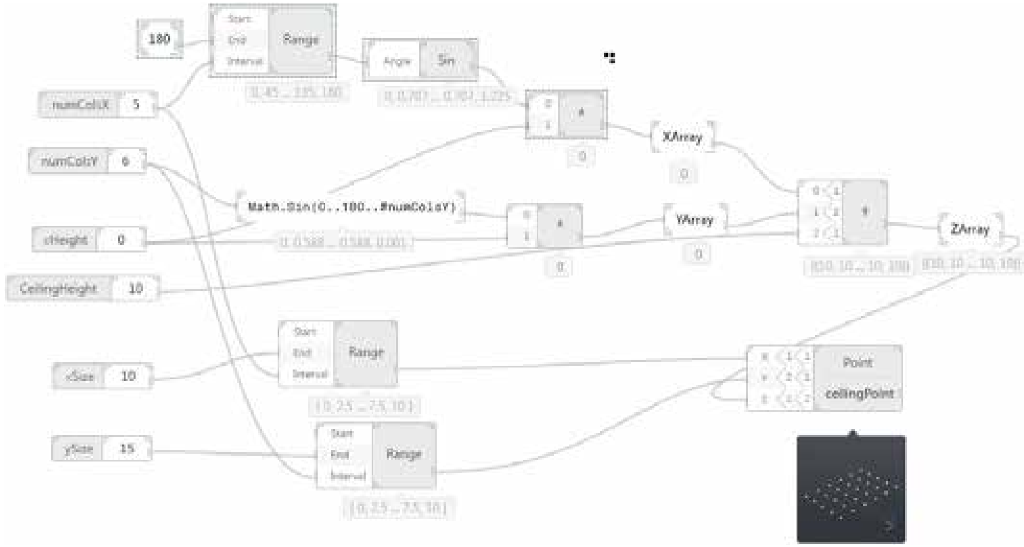

Figure 2
Starting with a conventional graph node diagram…

Figure 3
The designer select a region of the graph and use the marking menu…

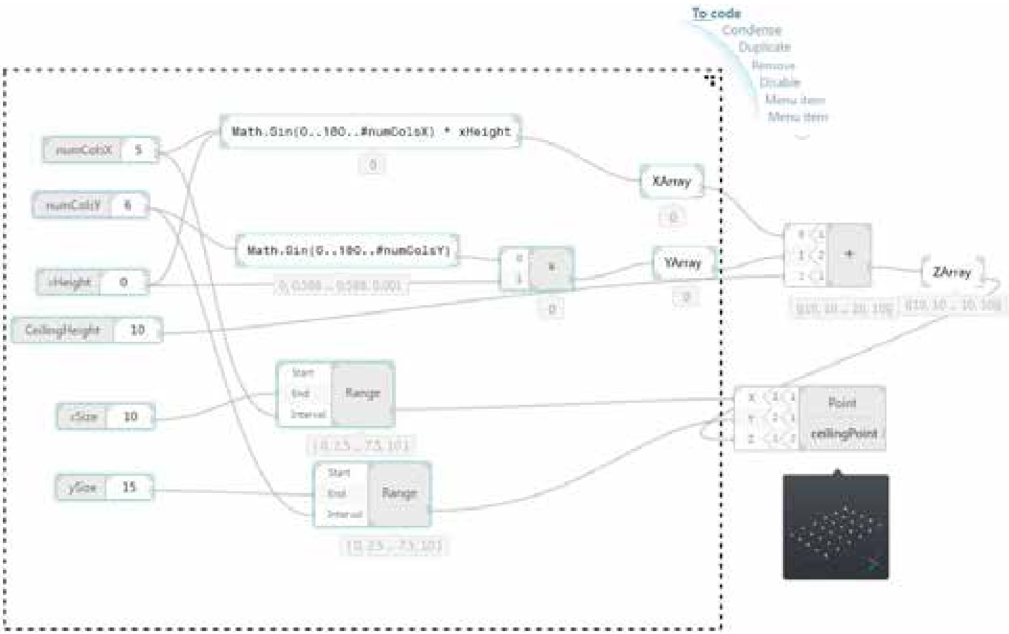

Figure 4
To turn the "nodes into code"…

```
xHeight = 5;

numColsX = 5;
XArray = Math.Sin(0..180..#numColsX) * xHeight;

numColsY = 5;
YArray = Math.Sin(0..180..#numColsY) * xHeight;

ceilingheight =10;
ZArray = XArray <1> + YArray <2> + ceilingHeight <1>;

xSize = 10;
ysize = 15;

ceilingPoint = Point.ByCoordinates ((0..numColsX..#xSize), (0..numColsY..#ySize), ZArray);
```

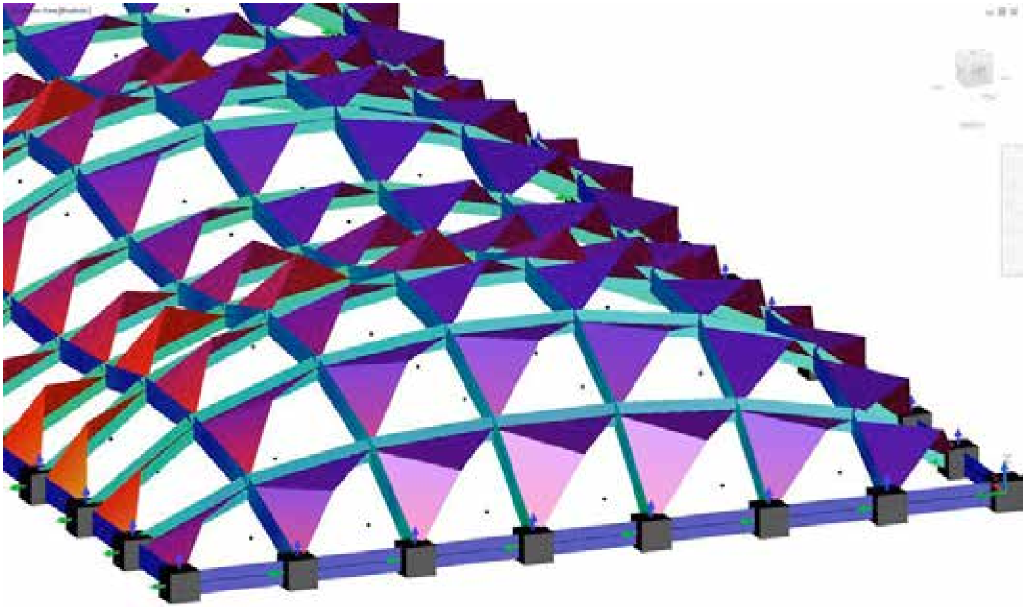

Figure 5
An example of a multi-disciplinary design model created with DesignScript, using a mix of simulation and analytical techniques provided by the different available plug-in's, including: form finding [with SmartForm], structural analysis [with Robot] and insolation on the shading devices [using Performative Design]. The colour coding on the structural members indicates structural utilization, while the colour coding on the shading devices represents insolation. Note: the structural nodes on the periphery are fixed, the ones in the centre are free to find their correct position.

On the one hand there are advantages in having design applications support more domain specific functionality: not in isolation, but rather integrated into a single common application framework and capable of acting as a computational intermediary between the different members of a multi-disciplinary design team.

On the other hand there are advantages if design applications could step back from being too domain specific and support a 'return to first principles' by exposing both computational and geometric abstractions directly to the designer.

Scalable to projects of different size and complexity

Design concepts often start as disarmingly elegant and simple ideas which can easily be explored with lightweight models or scripts. But to be realised as a physical building, these ideas necessarily have to be developed into complex building models with hundreds of thousands of individually detailed components.

In some cases the 'concept' is the overall form of the building, but increasingly the design concept may be an engineering principle or an objective to achieve a particular combination of performance metrics, or the use of a particular generative algorithm distributed within the individual components. In these latter approaches to the design, the architectural 'form' may emerge as a consequence of the design process rather than imposed 'top-down'. In addition, the resulting design representation may not be a traditional 'building model' primarily intended to support conventional drawing extraction. Rather it may be a series of 'geometric normalisations' intended to be the minimum information required for a direct digital fabrication process or robotic construction. Indeed conventional workflows (or data flows) are being supplemented by innovative project specific processes. Because of the essential 'open-endedness' of this new form of design, it is increasingly important that design applications are similarly 'open-ended'.

Summary

In summary, DesignScript is a computational system which is intended: to support the progressive acquisition of computational skills, to encourage the integration of different design disciplines and to support projects of different size and complexity.

Whatever changes occur it is important that the computational application can accommodate these changes and maintain a common underlying representation of design logic with no loss of fidelity, capability or performance.

DESIGNSCRIPT AS A DOMAIN-SPECIFIC LANGUAGE

Graph node diagraming is now a well established technique in design computation. The intention of a graph node diagramming user interface is to provide the designer with an intuitive and easily used 'proto-programming' tool that requires little or no previous understanding of programming concepts. Many of the existing applications which support a graph node style of computational design have made a separation between this type of interactive dependency modeling and regular scripting using conventional imperative languages such as Python, C# and Java.

Effectively, graph node diagramming is a form of 'data flow' programming which has developed independently of conventional programming languages. The intention of DesignScript is to explicitly recognise graph-based dependency modelling as a form of 'associative' programming. We can define an associative programming language as one which represents data flow in a human readable text notation. DesignScript supports the display and interaction with the underlying dependencies via both graph node diagramming and a corresponding text based associative language.

Indeed, while the designer is using graph node diagramming he may not be aware of that the graph is being recorded in DesignScript. But as the designer progresses and wishes to explore more complex modeling tasks he will necessarily need to acquire a more formal understanding of programming and design computation. The 'node to code' transition process is an extremely powerful way of using the result of an initial 'graph modeling' as the starting point for scripting, but there are still some challenges facing the designer to acquire the underlying programing concepts if he is to harness more of the potential of scripting. The following discussion might serve as an introduction to these issues and extends the previous work (Aish, 2011; 2013).

Within a domain specific application, such as DesignScript, we need to distinguish between the functionality related to particular 'domain-specific' objects such as walls, windows, columns and beams which typically would be implemented in specialised application libraries, and more general functionality that would be implemented at the language level. In this context a domain-specific language implements many of the facilities found in general purpose programming languages. In addition, a domaim specific language takes more general concepts from the application domain and promotes these concepts to be 'first class' features of the language (Table 1).

DesignScript could be described as a hybrid language which implements familiar concepts (and syntax) found in imperative, functional and object oriented languages and combines these with a number of new innovations in the form of an associative language.

The essential hybrid 'associative-imperative' nature of DesignScript is illustrated in the way it combines two domain specific ideas. First, the idea of a building being composed of a series of dependent collections of components where some members have special conditions' (typically supported by graph node diagramming and its representation as an associative language). Second, the idea of 'designing' as an exploratory activity which involves iterative refinement (as supported by iteration and conditional logic found in conventional imperative languages).

The differences between Associative and Imperative programming

Both Associative and Imperative languages have executable statements, for example:

domain-specific example	programming concept	implemented
create an array of objects	collections	DesignScript Associative language
zipped operations on collections	replication	DesignScript Associative language
cartesian operations on collections	replication guides	DesignScript Associative language
one object depends on another object	dependencies	DesignScript Associative language
modify an object [could be a sub-set of a collection]	multi-state modifiers	DesignScript Associative language
iterative refinement	iterative, **for** or **while** loops	standard imperative languages
conditional logic	**if.. else** statements	standard imperative languages
group a series of actions as a single composite action	encapsulation	standard functional languages
create a new specialised type of object	class inheritance	standard object-oriented languages

Table 1
DesignScript as a 'domain-specific' languages implements many of the facilities found in general purpose programming languages and adapts these for a domain-specific purpose and in addition takes more general concepts from the application domain and promotes these concepts to be 'first class' features of the language.

a = 10;
*b = a * 2;*
.
.
a = 20;

In the case of an imperative language, the final statement *a = 20;* does not cause the previous statement *b = a * 2;* to be re-executed.

In the case of an associative language, the statement *b = a * 2;* is not just an executable statement, it is also records a persistent dependency relationship between variables *b* and *a*, such that any change to *a* will automatically force a re-execution of all statements where *a* is referenced on the right hand side, as in *b = a * 2;*.

Imperative programming uses special 'flow control' statements, such as **for** and **while** loops and **if .. else** statements. These flow control statements are independent of the executable statements. In the absence of any flow control statements imperative programming executes statements in the sequence of the source code (i.e. in the lexical order). Associative programming does not have separate flow control statements but instead uses the concept of dependencies inherent within each statement (such as to *b = a * 2;*) to create a topological ordering of all the statements. The statements are then executed in this topological order.

In addition, associative programming within DesignScript also introduces two further concepts: 'replication' (in various forms) and 'modifiers'. The full power of DesignScript emerges when the graph based dependencies, replication and modifiers are all combined. These are discussed in the following sections.

Replication

In many existing programming languages a distinction is made between a single variable of a particular type and an array or collection of that same underlying type. This distinction restricts the interchangeable use of a collection or a single value of the same underlying type and forces the programmer to write different code for a single variable and for arrays or collections.

One of the domain-specific aspects of DesignScript is to relax this restriction and make the language more flexible and more tuned to its use by novice programmers. In this context, DesignScript introduces the concept of 'replication'. With replication, anywhere a single value is expected a collection may be used instead and the execution of the statement containing the collection is automatically executed for each member in that collection.

The combined result of dependencies and replication is that it is easy to program complex data flows (including geometric operations) involving collections. An upstream variable may change from being a single value to a collection or from a collection to another collection of different dimensions or size. As a consequence, the downstream dependent variables will automatically follow suit and also become a collection of the appropriate dimension and size. This makes associative programming incredibly powerful, particularly in the context of generating and controlling design geometry. It avoids the designer (as a novice programmer) from being pre-occupied with the size or dimensionality of variables.

Zipped replication

When there are multiple collections within the same expression we need to control how these are combined. With 'zipped' replication, when there are multiple collections, the corresponding member of each input collection is used for each evaluation of the expression. This works well when all collections are the same dimension and length. If collections are of different lengths, then the shortest collections determines the number of times the expression is evaluated, and hence the size of the resulting collection.

```
a; b; c;    // define the variables to be output at the top
or outer scope
 [Associative]
{
   a = {1, 5, 9};
   b = {2, 4, 6};
   c = a + b;    // zipped replication operation .. c = {3,
9, 15}
}
```

The equivalent imperative code would be:

```
a = {1, 5, 9};  // define the variables to be output at the
top or outer scope
b = {2, 4, 6};
c;
[Imperative]
{
   n = Math.Min(Count(a), Count(b));
   for (i in 0..n)
   {
      c[i] = a[i] + b[i];
   }
}
// c = {3, 9, 15}
```

Cartesian replication

When there are multiple input collections we need to control how these are combined. With 'cartesian' replication, all members of all collections are evaluated so that resulting collection is the 'cartesian product' of the input collections.

DesignScript introduces a special notation called 'replication guides' to control the order in which the cartesian product is created and takes the form <*n*>, where *n* defines the sequence of the replication operations. This sequence is equivalent to the order of the nested *for* loops that would have had to be written in an imperative script.

```
a; b; c; d; // define the variables at the top or outer sco-
pe
[Associative]
{
   a = {1, 5, 9};
   b = {2, 4 };
    c = a<1> + b<2>;  // cartesian replication  c = { { 3, 5
}, { 7, 9 }, { 11, 13 } }
   // changing the sequence of replication guides chan-
ges the resulting collection
   d = a<2> + b<1>;  // d = { { 3, 7, 11 }, { 5, 9, 13 } }
}
```

The equivalent Imperative code would require doubly nested *for* loops. To compute *c* the outer loop would iterate over *a* and the inner loop would iterate over *b*.

```
a = {1, 5, 9}; b = {2, 4, 6}; c; d;  // define the variables at
the top or outer scope
[Imperative]
{
   m = Count(a);   n  = Count(b);
   for (i in 0..m)
   {
      for (j in 0..n)
      {
         c[i][j] = a[i] + b[j];
         d[j][i] = a[i] + b[j];
      }
}
// c = { { 3, 5 }, { 7, 9 }, { 11, 13 } }
// d = { { 3, 7, 11 }, { 5, 9, 13 } }
```

Modifiers

With modifiers each variable can have multiple states which might be used to create a geometric modelling sequence. For example a geometric

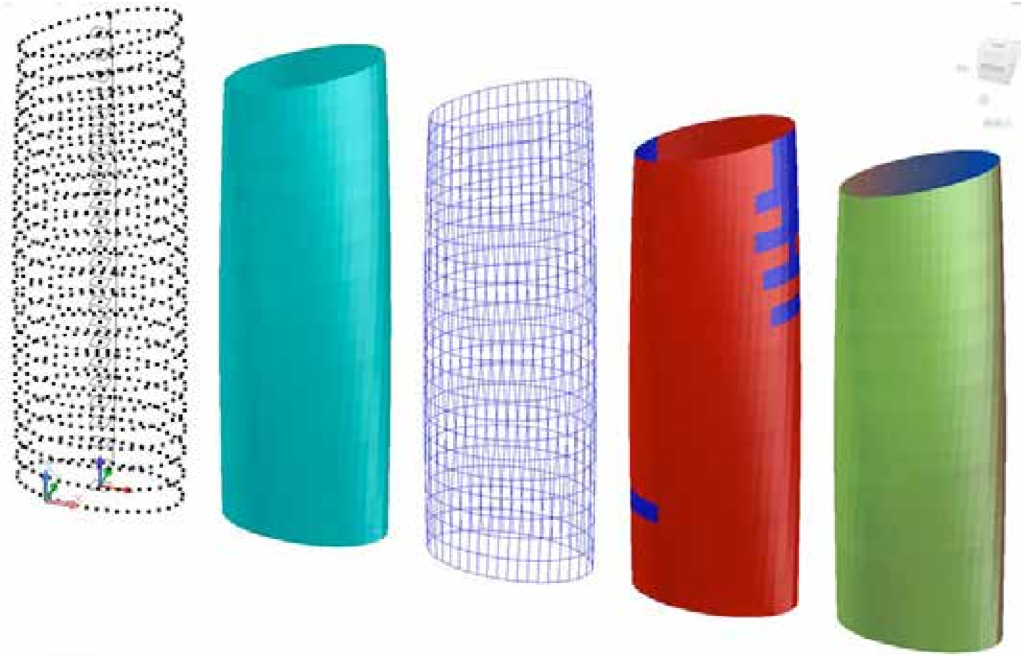

Figure 6
Façade design and analysis with DesignScript, showing the development of a conceptual building model as a series of polygons. Those polygon which are significantly 'out of plane' can be visually identified [indicated in blue in the model, second from the right] and this condition can be used in a downstream fabrication process, for example by switching to different types of facade panels.

variable might be created (say as a curve) and then 'modified' by being trimmed, projected, extended, transformed or translated. Without the concept of modifiers each state or modelling operation would require to be a separate variable and this would force the user to have to make up the names of all these intermediate variables. Modifiers avoid imposing this naming process on the user.

Combining dependencies, replication and modifiers

Dependencies, replication and modifiers can all be combined to represent the typical modeling operations found in architecture and constructions. Buildings are composed of collections of components. Typically these collections are often the product of a series of standard operations across all members. On the other hand, within such collections there may be special conditions where different or additional modeling operations are required to be applied to a sub collection of members. Modifiers enable these special conditions to be identified and the additional modelling operation applied.

To give an example, imagine that a building façade is based on a set of polygons. The polygons will be the 'support' geometry for the façade panels. However, in this example those polygons which are 'out of plane' by some critical dimension require a special modification before being used as the support for the corresponding facade panels (Figure 6).

The designer may want to apply a special operation but only to the 'out of plane' polygons and the application of this operation should not alter the particular polygon's membership of the collection of polygons. In this context all the polygons have a common defining operation, but some polygons have an additional 'modifier' operation applied.

Having applied the special modifier operation to the specific polygons, the designer can use the whole collection of polygons to generate the collection of façade panels. The collection of façade panels is dependent on the heterogeneous collection of polygons. Additionally, the designer may want to embed the whole polygon collection and façade panel generation process in an iterative loop to optimise the design for some criteria, such as solar gain, structural efficiency.

While this example is reasonable 'domain-specific' (dealing with polygons and facade panels), the fundamental ideas (of collections, modifiers and dependencies) on which the DesignScript language is based are necessarily quite abstract.

CONCLUSION

DesignScript is intended to address many of the critical issues in contemporary design practice, including the progressive acquisition of computational skills, the shift to multi-disciplinary integration and scalability of projects.

At one level DesignScript is an intuitive application which can be used by designers (as novice programmers) with the minimum programming prerequisites. Yet behind this intuitive user interface is a highly innovative programming language that introduces a number of domain-specific programming ideas including associativity, replication and modifiers. These innovative ideas are combined with well established conventions drawn from imperative, functional and object oriented programming languages and unified into a single scalable computational design application. A special characteristic of the user interface is that it supports the progression from novice user to more accomplished programmer by progressively revealing or unmasking these underlying computational concepts.

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Performative Design

Architectural Thermal Forms

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Abstract. *The paper presents a developed method and algorithm to create environmental sustainable optimised forms based on the solar energy received in relation to receiving, containing and distributing energy. Different studies are created based upon this approach, to which forms are evaluated against conventional building geometries. The work shows a significant improvement on several aspects of environmental performance. Lastly the work presents an idea of maximum structures, rather than minimum structures as a path in future research work.*
Keywords. *Sustainable environmental architecture; performative generative algorithms; simulation; material distribution.*

INTRODUCTION

The overall form of a building describes not only its architectural language, but also to a large degree its capacity to become environmental sustainable in relation to its local climatic environment. Movement of the sun in relation to the Earth, its surface orientation and its mass constitute the weather condition locally and globally as it regulates air flow, heat accumulation, heat transfer etc. (Oke, 1987). These relations, solar geometry and mass, form the environment for life and its rhythms. The solar environment is thus the singular most important factor in relation to climatic environmental architecture.

The creation of architectural building forms as derivatives of the solar environment has thus the potential of improving the context specific reception and containment of energy towards environmental sustainable architecture. If the position of the sun in relation to Earth surface orientation and its mass properties can determine local environments as briefly described above, then the same could be activated as a strategy for the generation of sustainable environmental architectural forms and their mass properties. The argument that form and distribution of material has the ability to lower the energy used in a building with up to 80% (Petersen, 2012), combined with the urgent need for environmental adapted architecture motivates the research.

Previous work

A recent trend in sustainable buildings in northern climates has largely been designed to minimise surface to volume relations, while increasing energy uptake, as seen in the Lighthouse project from 2009 by Christensen & Co Architects. It uses its circular form as an optimum sustainable geometry [1]. While currently being an advanced example of sustainable architectural form in the built environment, design of architectural forms remains largely based on 'simple' design principles.

Digital techniques in simulation and generation of architectural form have evolved rapidly over the last decade enabling the handling of complex climatic, geometrical and manufacturing aspects. The ability to construct advanced generative formal organisations have been shown in works by architects Marc Fornes [2] and Roland Snooks (2011) through growth systems and swarm systems. Other complex arrangements of forms are created in the work of Alisa Andrasak (2006) and Jenny Sabin (2008) to just name a few. The methods and techniques from above exhibit individual potentials with different objectives and at various scales. Common, is the descriptions of local and relatively simple rules that govern larger assemblies into elaborate structures. Today, a plethora of projects and a growing group of people develop generative systems that construct a formal output.

The work presented here continuous in the path of generative architectural methods and systems, but develop and connects these efforts explicitly with the generation of form in relation to the climatic environment based on solar-earth-mass relations.

Presented work

This work applies digital computation as an instrument for simulation of environment and material behaviour and generation of architectural form from this information. With an application of generative digital models with an integrated solar analysis that progressively add material in relation to receiving and containing energy, architectural forms are created as a derivative of the solar parameters. This intents to construct both an improved platform for sustainable environmental architecture and a context related architectural expression. The presented research investigates the capacity to create sustainable environmental architectural forms that are a response to a process of encoding a 6-dimensional factor space, constructed from x,y,z coordinates, time, material properties and solar climate. It does so by application of material properties into digital construction elements (points, geometrical entities), thereby linking physical parameters to iterative digital generative studies.

METHODS

The research applies a series of methods. Computation is used to simulate solar energy and thermal storage based on established mathematical models. This is combined with a developed generative method presented here, which distributes matter in space, progressively resulting in potential architectural forms. Lastly the generated forms are evaluated in a comparative analysis to conventional building forms.

Solar simulation

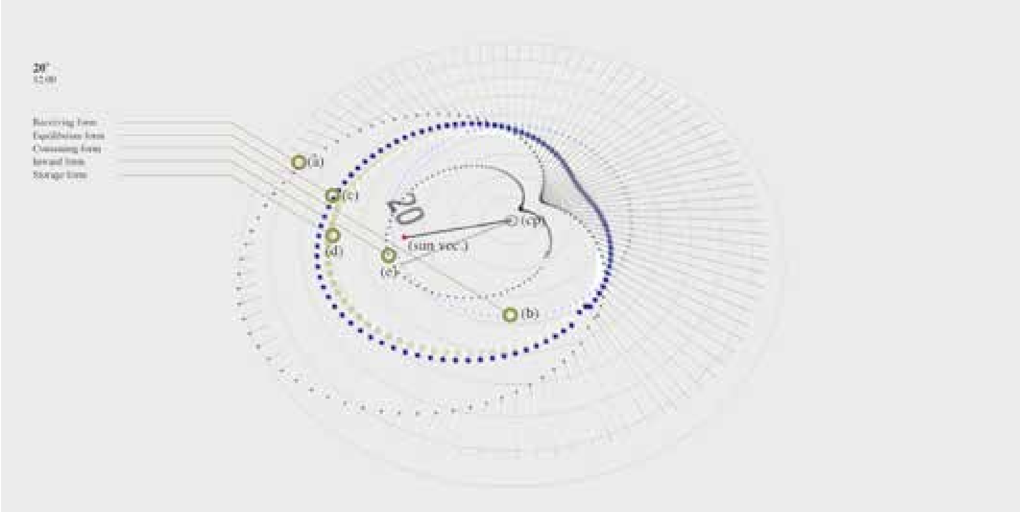
The encoded solar irradiance analysis is based upon geometrical relations described in *Lambert's Law* (Oke, 1987). Through the direct integration of the solar geometry, azimuth and zenith angles, and thus solar energy, the variables of location can be dynamically changed within the generative model described below. The simulated surface of the distributed elements is always facing 'outward' as the model intents to form closed structures.

Constructor: Matter distribution, creating form algorithm

With the intention of improving the holistic performance by solar energy, thermal forms are based upon the combined aspects of receiving, containing and transferring energy. Receiving energy requires an extended surface towards the energy source, following Lambert's Law. Containment in architecture is based upon minimum transfer of energy from the inside to the outside, therefore minimising the surface to volume ratio. Transfer of energy is related to the ability to move the energy received at the surface to the core of the form.

Based on these factors, an algorithm can be described which is based on 'the more energy received on a surface of an element, the longer from the core the element can be positioned', Figure 1. The following element created undergoes the same evaluation but rotated around a center point to position it next to the previous element. The longer the elements are positioned away from the centre point (cp) the

Figure 1
Distribution of solid matter from centre point according to energy.



longer distance is between the elements, effectively extending the combined surface oriented towards the energy source. The progressive formation creates elements (a). Following a similar method but with a fixed distance between a centre point and a created element form a circular form with optimum surface volume relation. The progressive formation creates elements (b). The formation located between elements (a) and (b), denoted elements (c) serve as an equilibrated formation. In the studies performed in this paper, (c) is always half the distance between (a) and (b). From (c) solid matter is distributed according to the description below.

Constructor: Matter distribution, creating mass algorithm

Following the creation of form, material properties are applied to the generative model through three different aspects, 1) u-value, the heat transition coefficient, 2) g-value, the solar gain coefficient and 3) thermal mass. These are selected based on their direct reference to established architectural terminology, and from sensitivity analysis of the most influential passive factors for sustainable architecture (Petersen, 2012).

The factors are plotted into a scheme, Figure 2, in relation to solar irradiance from above. The scheme is related to the northern hemisphere, in which southern orientations are effected by higher solar gain. In case of high irradiance materials that allow high solar gain can be low etc. The scheme could be reconfigured for other locations and paired with the above form creation algorithm generating other results than presented below.

Merging the above into one model, we have the following algorithmic procedure:

1. Distribute test elements around center (small inner circle around center point)
2. Calculate element angle vector from center to distributed element
3. Calculate sun vector
4. Calculate angle between element (a) vector and sun vector
5. Calculate radiation energy on each element based on Lambert's Law
6. Distribute elements from center based from quantity of solar energy at each test
7. Distribute element (b) from center with same radii creating circle
8. Calculate distance between elements (a) and

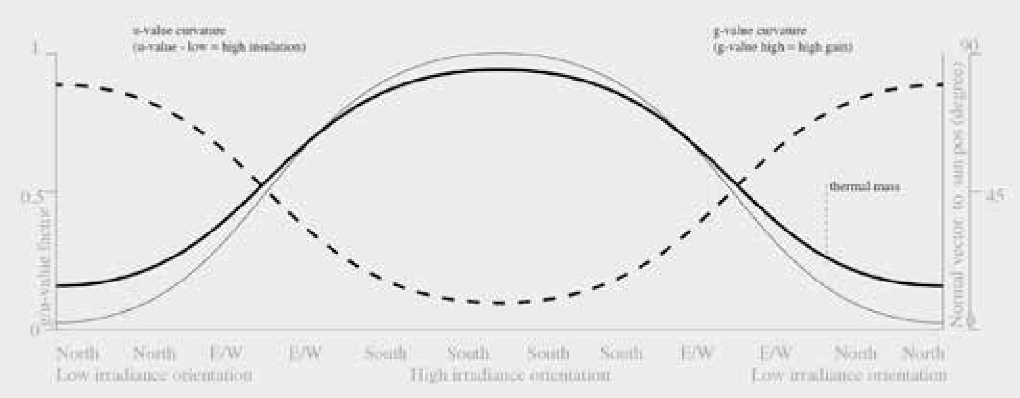


Figure 2
Distribution of mass at elements according u-value, g-value and thermal mass factors.

elements (b)

9. Distribute elements (c) between elements (a) and elements (b) as equilibrium
10. Calculate angle between element (c) and sun vector
11. Calculate radiation energy on each element based on Lambert's Law
12. Calculate optimum g- and u- value materials according to g-u-value scheme
13. Distribute elements (d) and scale/colour elements from calculated g- and u-
14. values
15. Calculate stored energy in elements (d) based on material property and
16. received energy
17. Calculate radiant energy emitted from energy stored in elements (d)
18. Distribute elements (e) towards center based radiant energy
19. If, elements(a,b,c,d,e) angle > TWO_PI move elements(a,b,c,d,e) up with
20. distance (z)
21. Return to (1)

Studies

Following studies are done from above developed algorithm.

Study A, mass is distributed based upon calculated optimum u-and g-values indicating what properties a given material should have when located at the given position computed by above method. This has the intention of suggesting a distribution of material and its properties not restricted to accessibility of contemporary materials, Figure 3a.

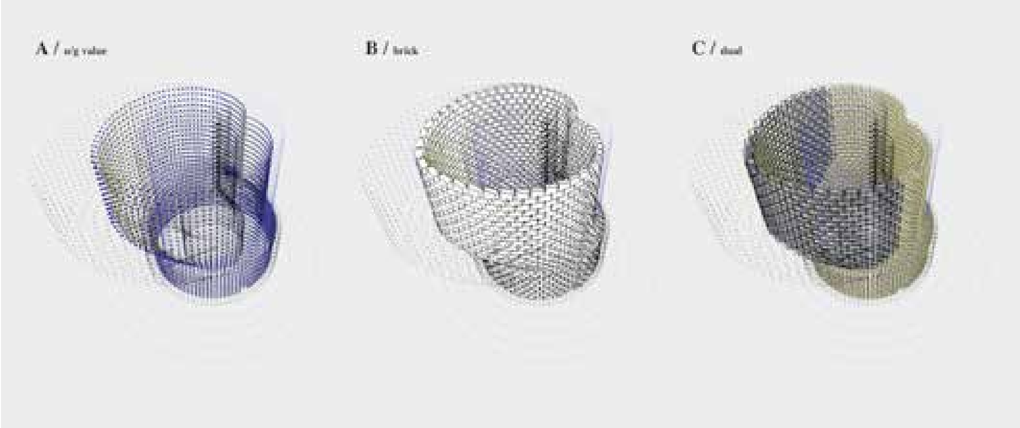
Study B, thermal properties of bricks (solid mass in geometric entity) is applied in the calculations of thermal storage in the organised form and causes a scaling of the brick. This has effect on the subsequent distribution of thermal material to locally scale reception and further distribution of heated air (fluid matter). This is done with the intention of only applying material where it is needed, Figure 3b.

Study C, evaluates the solar energy on a given surface and suggest from two materials, high and low energy absorption, which material to apply where. This has the intention of making the environment choose a material from a potential (small) catalogue of available materials, Figure 3c.

Comparative analysis

In order to understand the performance of the forms generated, a comparative analysis is done between conventional building forms and the forms derived from the method and algorithm. The comparison is provided on below eight aspects measuring the relations between receiving, using, storing and transferring energy in simple measures.

Figure 3
A,B,C. Distribution of solid matter from elements (c) as thermal storage according to energy.



RESULTS

The formations created by the developed method and algorithm illustrates clearly a circular form with a low application of thermal mass when the sun is high on the sky. In climates with a lower sun angle the form equilibrates into advanced forms with extended surface towards the source and decreased surface in the opposing direction. This is particularly evident when observing the formations 'live' or as one can see in figure 3 a,b,c where the sun was set in first 1/3 of the formation high on the sky, 85 degrees. The following 1/3 part of the formation the sun gradually lowered to a resulting angle of 6 degrees creating the transitional form to the last 1/3 of the formation where the sun is kept at 6 degrees.

In lower solar angles the most non-circular results are seen and therefore creates the largest differences to conventional building forms. Within the comparative analysis it is clear to see the performance in relation to the combined factors of receiving, containing and transferring energy, with significant improvements achieved based on the presented method.

Based upon the thermal matter volume distributed on the generated surface a heterogeneous surface structure density was created resulting in an organisation of solid matter only where needed. In figure 4, this has a large effect when compared to conventional methods of applying material homogeneously on all outward facing surfaces.

CONCLUSION

Based upon the presented studies we can suggest that energy optimum forms cannot be generalised to e.g. circular forms, but are much more a result of localised factors constructing the environment. If an urban environment were included this environment would perform different due to the change of casted shadows from neighbouring buildings.

If considering a tall and dense urban environment, where little to no direct radiation would occur, the hierarchy of factors could change, meaning the equilibrated form (elements c) could have a stronger 'weight' towards the energy containing form (elements b), rather than energy receiving form (elements a), as the energy for reception is not accessible. This, as a consequence, would create forms in dense urban areas that are more uniform circular than curvilinear oval forms as shown above. As the form rise above neighbouring buildings the 'weights' could alter again towards a hierarchy where reception of energy was favoured, resulting in very modified geometry compared to the perfect circle. This is what we see in figure 3abc.

The model, beyond the overall form, also introduces the calculation of a floor plan depth by how

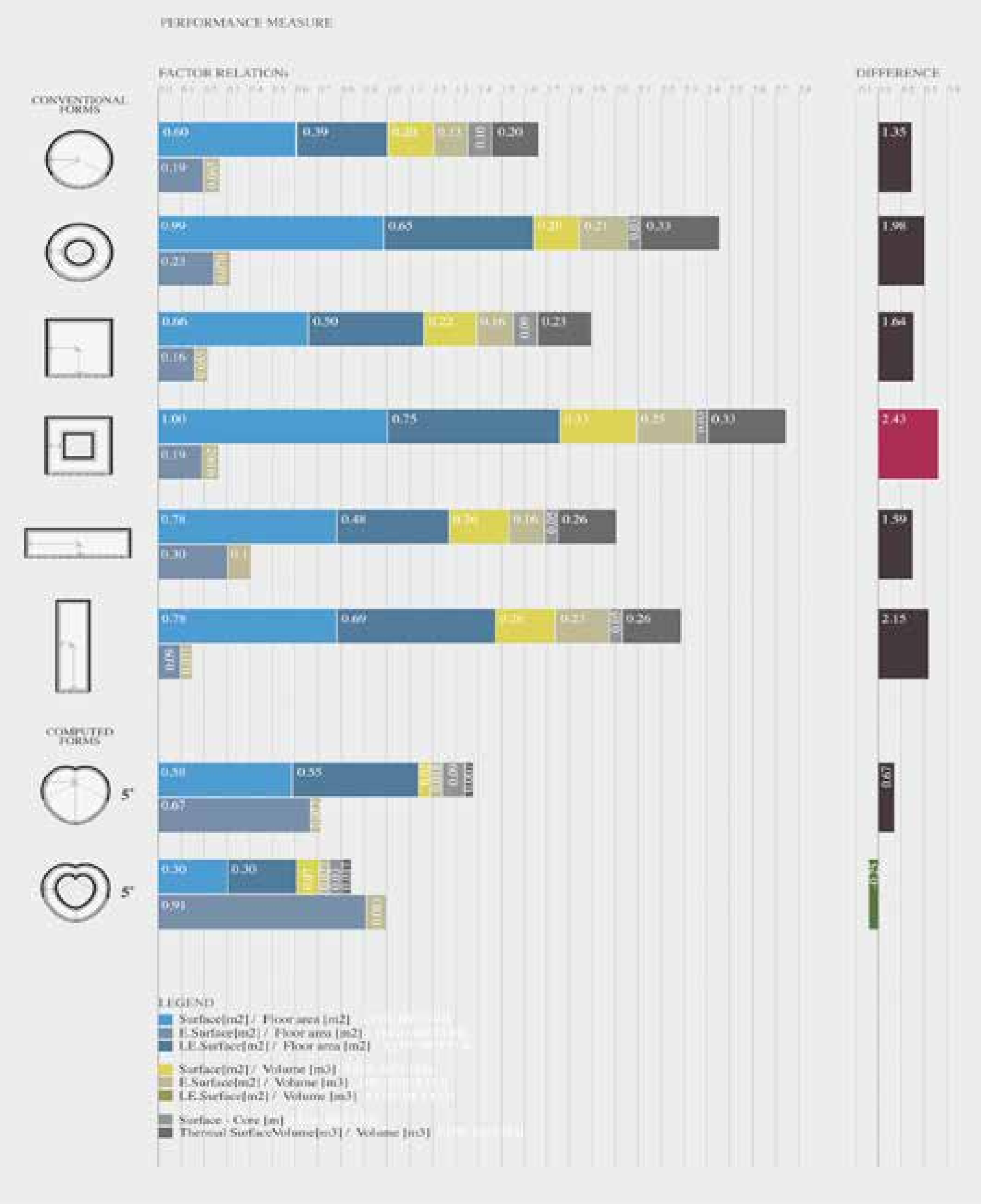


Figure 4
Comparative analysis between conventional building forms and the computed forms.

long the energy potentially could be transferred into the building after reception at the envelope. If further developed, this approach could suggest internal spatial organisation and divisions according to light levels needed, operating temperature, and spatial programme when considering the occupier as an environmental source.

Introducing more sources of energy, such as air flow cooling the surface or internal loads of occupancy and equipment could in a reciprocal relation further alter the articulation of the generated architectural form as energy is created both on the inside and outside of the envelope.

DISCUSSION

The work follows the biological notion by Darcy W. Thompson (1992) that a *'form of an object is a diagramme of forces'*. Additionally, we might add that the local forces are derivatives of the local form it interacts with.

Architecture has, for good reasons of structural optimisation, had a singular focus of 'minimum structures' by a tremendously rich legacy from Frei Otto, Erik Reitzel and others. However, this work also suggest to embark on an approach that can be referred to as *'maximum structures'*, which not only focuses on minimisation of used material, but equally how it maximise its performative organisation in relation to environmental sustainable architectures.

Such an approach could be initiated by the presented method of distributing material properties, such as thermal mass, transparency, even tactility, to expand the performative and aesthetical instrumentality of the generative models. This again, would expand the factors involved, and suggest an added hierarchy of factors to the one used within this work by the mentioned sensitivity analysis for sustainable architectures.

The work is presented as environmental performative forms, but as the built environment changes through urban reconstruction over time, the local climatic environments alter with it in a reciprocal manner. This suggests that the approach could be expanded into a more responsive structure, which by above method could suggest new forms, but with an underlying structural organisation that would allow for a dynamic adaptation resulting in changing the overall form of the building.

A less drastic approach in relation to moving structure adaptation could be performed locally at the material scale, directly utilising the presented method of material property distribution. This would require that the time-based adaptive properties, such as phase-change-materials where implemented in the initial generative process of distributing mass.

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DaylightGen: From Daylight Intentions to Architectural Solutions

Implementation and experimentation of a generative and parametric design tool

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Abstract. *This paper addresses the integration of the daylight effect during the early stages of the architectural design process. The first part presents a design assistance method that helps designers to characterize their daylight intentions and materialize them in architectural solutions. In this part, we describe the implementation of this method in a design tool, denoted DaylightGen, the implemented process and the different system components. The second part of this paper focuses on the investigation of the potential of the proposed method in design process. It was evaluated in educational design case study. This part integrates the experimentation process and his results.*
Keywords. *Computer aided architectural design; intentions oriented design; generative and parametric design tool; daylight simulation tool; design tool experimentation.*

THE *DAYLIGHTGEN* METHOD

This method proposes to help young designers to integrate their daylight effects intentions during the first step of the design process. The designer describes the daylight effects that he would like to integrate in his project. The described intentions are characterized and translated into potential solutions. The generated solutions will be used as a base line models to start the project design (Gallas et al., 2011).

The *DaylightGen* method is organized in five steps (Figure 1). The method process starts by the *"declare intentions (1)"* step where the designer describes his daylight intentions using a visual support. The designer uses pictures representing daylight effects to describe his own ideas.

He selects whose are corresponding to his intentions. The second step *"characterize intentions (2)"* of the method process aims to identify and characterize the designer's intentions. They are translated in a physicals and geometrical information that will be used at the *"solution generation (3)"* step. During this step the method will propose architectural solutions that create the described daylight effect and verify by the way the designer intentions. The solution

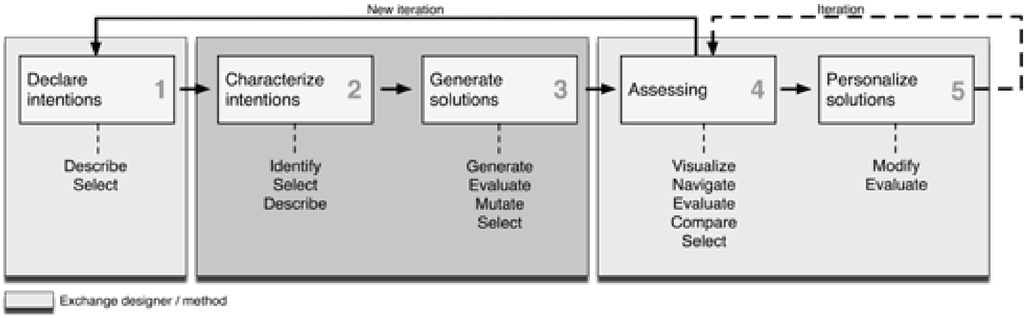


Figure 1
DaylightGen method process and activities.

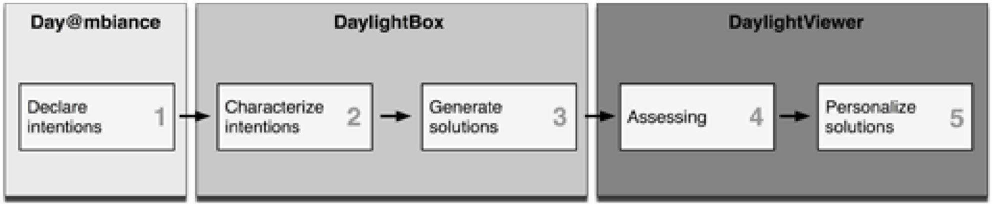


Figure 2
DaylightGen implementation tools.

generation step is organized as an iterative process of a *generation*, *evaluation*, *mutation* and *selection* activities. The fourth step of the *DaylightGen* method process is the *"assessing (4)"* step where the generated solutions are visualized and presented to the designer as a result of the *"generate solutions"* step. The "assessing" step integrates five activities where the designer *visualizes* and *navigates* in the collection of generated solutions, *evaluates* and *compares* them and finally *selects* the best ones. The method process ends by the *"personalize solution (5)"* step where designer could modify the generated solution features and transform them to integrate new ideas. The modified solutions will be visualized and evaluated with an iterative manner. The *"personalize solution"* step accompanies the designer and takes end when his is satisfied.

THE *DAYLIGHTGEN* TOOL

This method is implemented in a design assistance tool denoted *DaylightGen*. This prototype is composed of three tools: *Day@mbiance, DaylightBox* and *DaylightViewer*. Day@mbiance is used to implement the *"declare intentions"* step activities, *DaylightBox* materialize the *"characterize intentions"* and the *"generate solutions"* activities and finally the *DaylightViewer* integrates the *"assessing"* and the *"personalize solutions"* step's activities (Figure 2).

Day@mbiance

Day@mbiance is a navigation tool in a references images base proposed by Salma Chaabouni (Chaabouni et al, 2008). The images base is structured as a *MySQL*® database and managed by *Mamp*®. The navigation in the images base is realized by a *PHP*® application with a *Flex*® interface. A web browser (*Firefox*®) is used to visualize the *Day@mbiance* functions and results (Figure 3).

Day@mbiance is used to identify the designer daylight intention. Its process starts with a first

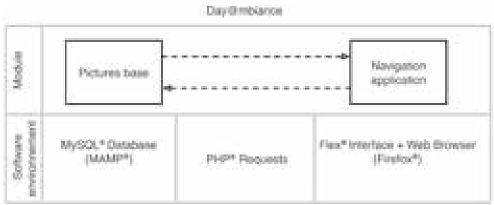
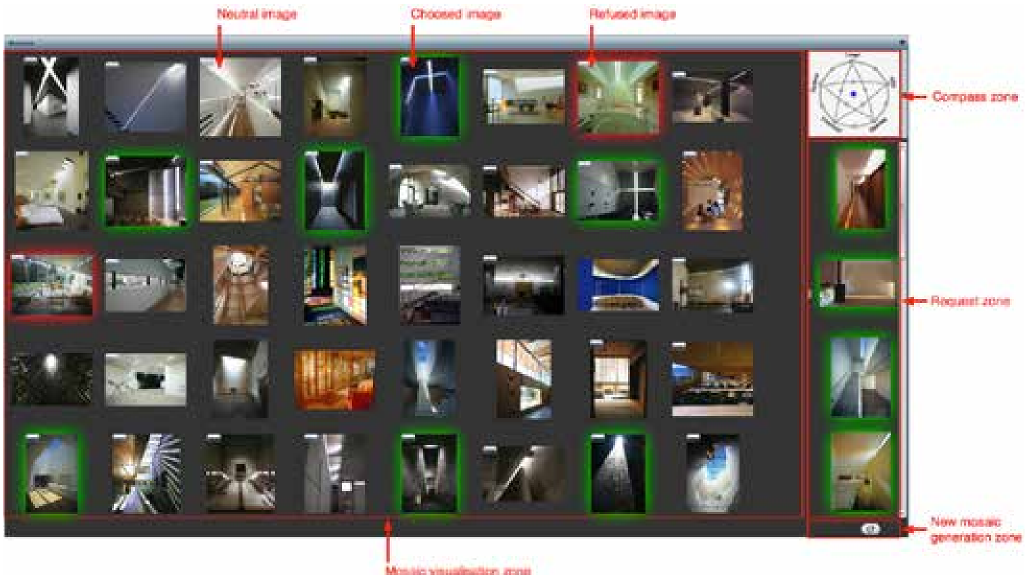


Figure 3
Day@mbiance implementation modules and environment.

Figure 4
Day@mbiance interface.



mosaic of images representing daylight effects. Designer chooses images that represent his intentions, refuses that are at the opposite and leaves others neutral to finally generate a new mosaic that takes into account his choices (Figure 4). All images are indexed by keywords that describe the visualized architectural configurations and daylight effects. This process will be repeated until the designer finds a collection of relevant images that corresponds to his intentions.

All images used by *Day@mbiance* are indexed using a keyword collection structured in a thesaurus. The thesaurus is divided in five facets that describe all images features: the daylight effect type, the quality, the quantity of daylight, the space surfaces aspects and the space function. The indexation process is realized by *Image* (software developed by Pascal Humbert form *MAP-CRAI*) (Figure 5).

The user's choice is then characterized a set of relevant keywords. The Keywords used to index the images has a pertinence weight that varies between -1 (not relevant) and 1 (relevant) (Halin, Créhange and Kerekes, 1990). When the designer choose an image, the pertinence weight of the keywords used to index it increases, when the image is refused the weight decreases and finally the weight stay the same if the image is neutral. The pertinence Weight of the keywords is used when *Day@mbiance* generate a new mosaic to take into account the designer preferences.

DaylightBox

The *DaylightBox* tool is implemented in *Rhinoceros®* modeler environment and his graphical algorithm editor *Grasshopper®* (Tedeschi, 2011). *DaylightBox* is a *Grasshopper®* definition that integrates six modules: a referenced images base *(Day@mbiance images base)*, a daylight effects knowledge base *(knowledge base),* a parametric model *(geometry)*, a generative algorithm *(Galapagos®)*, a daylight simulation tool *(simulation)* and a solutions database *(solutions storage)* (Figure 6).

The first module *"Day@mbiance imagse base"* is a *cluster* that integrates a plug-in to connect *Grasshopper®* to the pictures base used by *Day@mbiance*. This module selects the most significant keywords

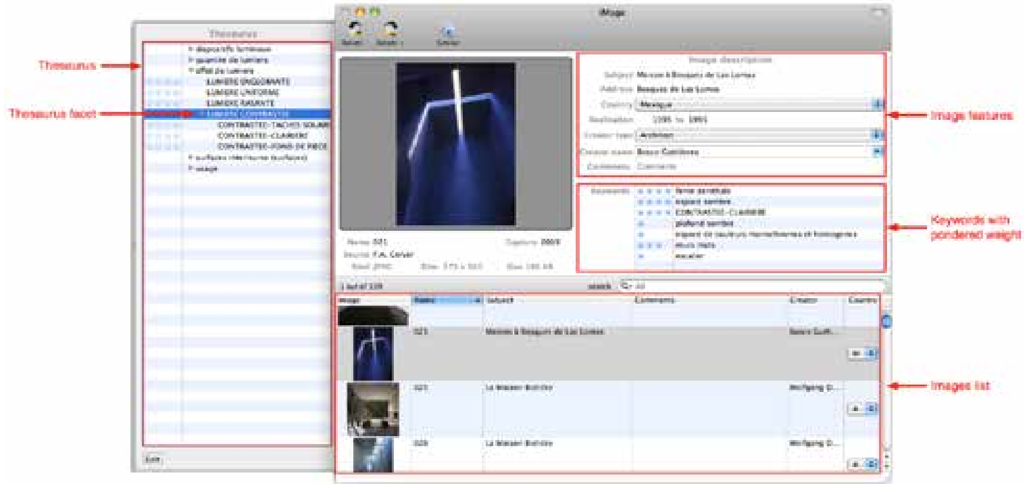


Figure 5
Picture indexation using "Image".

that characterize represented daylight effects in order to highlight the designer intentions. After that, the designer selects one of the identified daylight effects to start a solutions generation process. The second module *"knowledge base"* is used to identify and characterize the designer's intentions. This knowledge base contains the quantitative and qualitative features of different and recognized daylight effects. These features are integrated in a *fitness* function attached to each known daylight effect. It is composed of variables that characterize solar gains and their spatial distributions.

The third module *"geometry"* is a parametric model of parallelepiped shape defined by thirteen parameters (Table 1). These parameters define all the spatial features that influence the daylight behavior. The model parameters are implemented in *sliders* that determinate their data types and their variation ranges.

The fourth module is a generative algorithm *(Galapagos®)* that controls the parametric model features to generate solutions verifying the fitness value. The genetic algorithm uses the *fitness* function and his objective value (*fitness* value) to optimize

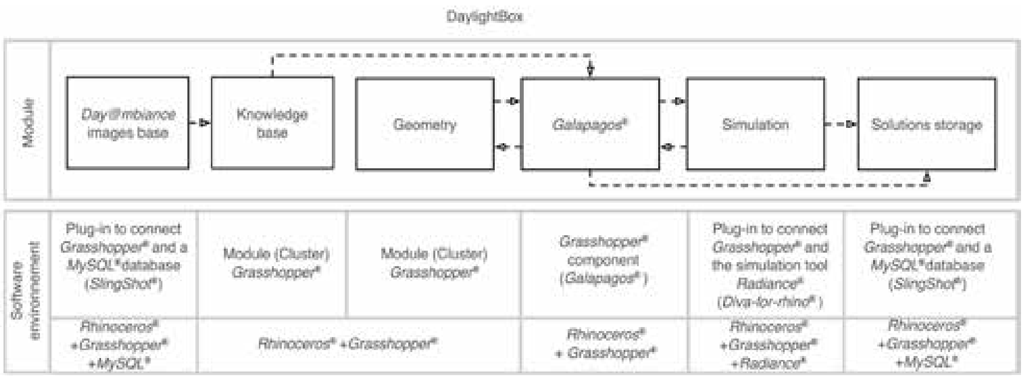


Figure 6
DaylightBox modules and software environment.

Table 1
Parametric model features.

Model parameters	Data type	Variation range
Dimension	Integer	250..750
Aperture rate	Floating	0..1
Aperture proportion	Integer	1..5
Aperture orientation	Integer	0..7
Aperture direction	Integer	0..1
Aperture number	Integer	1..10
Aperture position	Integer	1..11
Aperture face	Integer	0..1
Surface type	Integer	0..3
Aperture surface type	Integer	0..2

the solution generation process.

The fifth module *"simulation"* integrates the plug-in *Diva-for-Rhino*® (Jakubiec and Reinhart, 2011) to connect *Grasshopper*® to *Radiance*® simulation software. The system process iterate on a cycle composed of three main steps:

1. The genetic algorithm *Galapagos*® finds architectural parameters values using the selection, crossover and mutation operators. It optimizes the generated solution behavior and tries to reach the fitness value.
2. The parametric model *"geometry"* generates architectural models defined by the parameters values provided by the genetic algorithm.
3. The simulation module analyzes the daylight features of the geometry generated by the parametric model. The simulation results are used to compute the fitness value.

The generating process ends after a fixed number of generations. All the generated solutions features (parameters and fitness values) are stored in a *MySQL*® database using the sixth module *"solution storage"*. This module create a link between *Grasshopper*® and *MySQL*® using the *Slingshot*® [1] plugin.

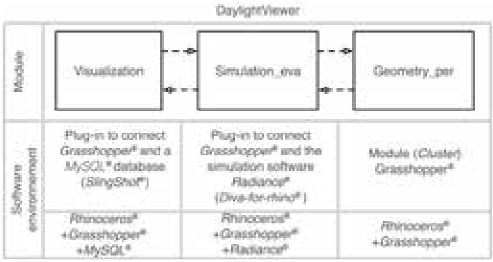


Figure 7
DaylightViewer modules and software environment.

DaylightViewer

The *DaylightViewer* tool is implemented in *Rhinoceros*® modeler environment and his graphical algorithm editor *Grasshopper*®. *DaylightViwer* is a *Grasshopper*® definition that integrates three modules: a visualization interface defined by the *"visualization"* module, a simulation module *"simulation_eva"* and the parametric model *"geometry_per"* (Figure 7).

The first module *"visualization"* imports the best solutions according to their *fitness* value (solution with the lower value of fitness). The selected solution are visualized and organized in a colored grid from the best to the worst one. The user selects the number of solution to visualize and navigate under the visualized solutions (using *Rhinoceros*® visualization windows) to select those corresponding to his intentions. The second module integrates a simulation tool that makes realistic and quantitative simulations in order to verify that chosen solutions produce the described daylight effect. The third module is composed of geometrical operators that could be used by designer to transform the proposed solutions. The module *"geometry"* presents the features of the selected solution and the list of sliders to modify the parameters values. The transformed solution could be evaluated (realistic and quantitative simulations) and exported it in 3D geometrical objects (bake them from *Rhinoceros*® to *Grasshopper*®) (Figure 8).

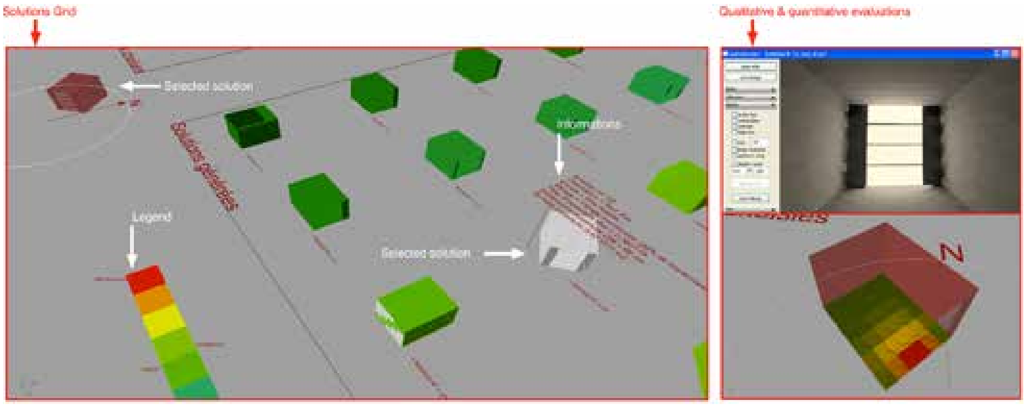


Figure 8
Solutions grid and evaluation visualization.

THE *DAYLIGHTGEN* EXPERIMENTATION

The third part of this paper assesses the *DaylightGen* tool contribution during the early design steps. We try to determinate:

- the adaptation level of the method activities and functions to the early design steps features,
- the capacity of the assistant method to take into account the uncertainly that characterize early design steps,
- the creativity level and the capacity of the method to help designer to explore new ideas,
- the capacity to satisfy and materialize designer intentions.

The potential of the method has been evaluated in an educational context. We proposed to 16 Master degree students in architecture to design a project by using the *DaylightGen* tool. They worked in pairs during three hours to design a temporary exhibition space dedicated to a designer *(Jean Prouvé)*. The project program is composed of two temporary exhibition rooms. The first integrates a graphics media describing the designer life. The second room is dedicated to the exhibition of models and some architectural components.

Experimentation process

The experimentation process is organized on three steps. The first step aims to prepare the participants to the experimentation activities. We organize a training sessions to present the experimental framework, the design assistance method targets and the utilization mode of the different components of *DaylightGen* tool (*Day@mbiance, DaylightViewer* and *DaylightBox*). The second step is organized in design sessions for duration of three hours where a pair of student tries to design a project sketch that express particular and significant interest to daylight atmospheres. The experimentation participants are authorized to use different sketch and modeling tools (paper format, *Photoshop*®, *AutoCad*®, *Sketchup*® and *Rhinoceros*®). All design sessions are captured on video to keep the student's discussions and the exchanges with the different tools (Figure 9).

The third step of the experimentation process aims to evaluate the participation of *DaylightGen* tool during the conceptual design phases. The evaluation step starts by analyzing the captured sessions. Analyzing the experimentation feedback questionnaire realized with all participants concludes the evaluation step. This online questionnaire [2] integrates questions about the different functions and the results obtained by *DaylightGen* tool.

Experimentation results

1. *Video capture analyze*

We determinate the design process used by the experimentation participants by analyzing the de-

Figure 9
Experimental device.

sign sessions videos. We identify the major design activities that participate to the design process and their chaining. All design activities and the design supports used are transcribed in time line diagrams (Figure 10). The diagrams analyze reveals three design approaches (Figure 11). The first one (used by group 1 and 2) starts by formulating design problem, implanting the project, formulating and declaring daylight effect intentions using *Day@mbiance*, identifying and selecting daylight effect, generating solution and proposing a spatial configuration for the project. The second approach (used by group 4-5-6-7) starts by formulating design problem, implanting the project, proposing a spatial configuration, formulating and declaring daylight effect intentions using *Day@mbiance*, identifying and selecting daylight effect, generating solution. The third one (used by group 3) starts by formulating design prob-

Figure 10
Example of design activities diagram.

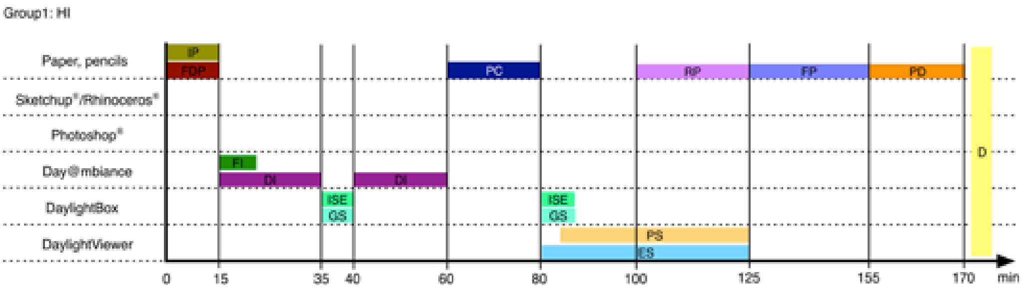


Figure 11
Design approaches.

Approach 1	Group 1-2	FDP	IP	FI	DI	ISE	SG	PC	ES / PS	RP	FP	PD	D
Approach 2	Group 4-5-6-7	FDP	IP	PC	FI	DI	ISE	SG	ES / PS	RP	FP	PD	D
Approach 3	Group 3	FDP	FI	DI	ISE	SG	IP	PC	ES / PS	RP	FP	PD	D

- FDP Formulating design problem
- IP Implanting project
- FI Formulating intentions
- PC Proposing spatial configuration
- DI Declaring intentions
- ISE Identifying and selecting daylight effect
- GS Generating solutions
- ES Evaluate solutions
- PS Personnalize solutions
- RP Reshape the project
- FP Finalize the project
- PD Project delivery
- D Debrief Experimentation

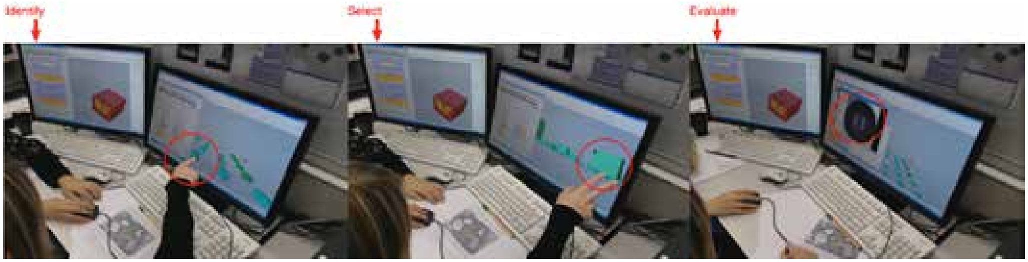


Figure 12
Identify, select and evaluate generated solutions.

lem, formulating and declaring daylight effect intentions using *Day@mbiance*, identifying and selecting daylight effect, generating solution, implanting the project and proposing a spatial configuration for the project. All design approaches ends by the same way: the designers evaluate and personalize the generated solutions, reshape the proposed project, finalize the project and debrief the experimentation session.

The participants on the experimentation use different design supports to formulate design intentions and materialize them in architectural solutions. They associate mosaic navigation activity, manual sketches and oral expression to precise the daylight effect intentions that correspond to the project constraints. The solutions grid generated helps students to explore and define new design issues. The navigation in solutions grid helps students to locate and identify interesting solutions that could be implemented in their projects (Figure 12). Students express their interest by manual gesture and some oral expressions like *"this is small, it concentrate daylight"* to identify and describe a solution with one small aperture in the corner or *"this is a jail effect"* to describe a solution with two long and fine vertical apertures in the right and left side of the aperture face. The students use the evaluation function to visualize the daylight effect generated by the selected solutions and verify if they corresponds to the described intentions. They operate different simulations at different times and for different sky conditions.

The navigation on the solution grid and the evaluation of the selected solutions gives to participant's new ideas that were integrated using the modification and personalization functions proposed by the *DaylightViewer* tool. They used these functions to combine different configurations and exceed the parametric model limits. The group 3 used the modification, the evaluation functions and *Photoshop*® to create a new architectural solution with apertures on three faces that could not be realized by the generative model (aperture only on one face) (Figure 13).

The best-generated and personalized solutions was integrated and implemented in the project by analogy. The final daylight effect generated was

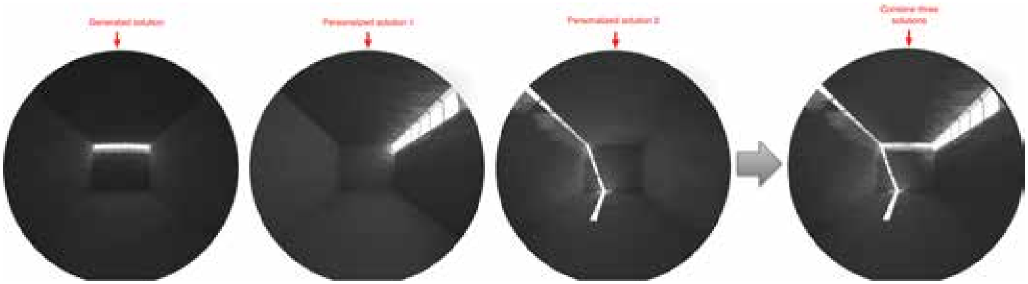


Figure 13
Combine generated and personalized solutions.

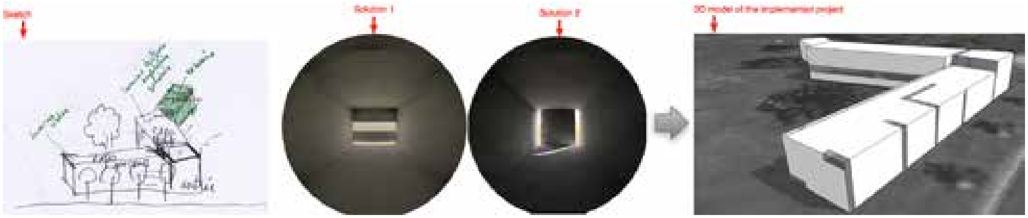


Figure 14
Generated and personalized solutions implementation.

evaluated using shadow visualization functions of *Sketchup*® and daylight simulation plug-in (*Diva-For-Rhino*®) of *Rhinoceros*®(Figure 14).

2. *Questionnaire answers analyze*

The questionnaire answers was used to identify what users think about the design assistance method and about the functions proposed by the different tool participating on the process. The main part of participants declares that the use of images to identify the daylight effect intentions is really adapted to the conceptual design steps. They say that images constitute a fist level of the implementation process of design intentions. The students are satisfied by the generated solutions that verify at different levels of accuracy the described intentions. Student's answers reveals that the parametric model used for the generation activities needs to integrate more apertures types and more precise functions (multiple aperture with different sizes and shapes, aperture on different surfaces, integrate personal architectural configuration in the generation process).

The majority of participants consider evaluation and personalization functions as very useful because they allow users to reshape proposed solutions and to integrate new ideas. Students consider that the evaluation of these new solutions helps designer to create an iterative process that makes the project design progress.

CONCLUSION

This paper presents the implementation process of the *DaylightGen* method, the choice of the software environment, the modules and the component used to create the design assistance tool. It presents also the different steps, devices and results of the experimentation process used to validate the *DaylightGen* method and tools targets. The experimentation results validate the capacity of the proposed method and tool to assist the daylight integration during early design steps. These results confirm the possibility to use the design intentions as basic information in design assistance tools. The experimentation results reveal some limits that concerns the number of identified daylight effects, the fitness function precision and parametric model possibilities that could be developed in future work. These results show that the proposed method could be ameliorated and adapted to a professional design context.

ACKNOWLEDGEMENT

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Performance Driven Design and Design Information Exchange

Establishing a computational design methodology for parametric and performance-driven design of structures via topology optimization for rough structurally informed design models

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Abstract. *This paper presents a performance driven computational design methodology through introducing a case on parametric structural design. The paper describes the process of design technology development and frames a design methodology through which engineering, -in this case structural- aspects of architectural design could become more understandable, traceable and implementable by designers for dynamic and valid performance measurements and estimations. The research further embeds and customizes the process of topology optimization for specific design problems, in this case applied to the design of truss structures, for testing how the discretized results of Finite Elements Analysis in topology optimization can become the inputs for designing optimal trussed beams or cantilevers alternatives. The procedures of design information exchange between generative, simulative and evaluative modules for approaching the abovementioned engineering and design deliverables are developed and discussed in this paper.*
Keywords. *Performance driven design; design information; design technology; topology optimization; parametric design.*

INTRODUCTION

One of the challenges in performance driven design methodologies is the way that designers can effectively integrate simulation and optimization techniques with parametric design and generative procedures (Oxman, 2008). This challenge can also be attributed to as the lack of tools to support effective knowledge integration in Computer Aided Design (CAD) techniques and methods (Cavieres et al., 2011). In design practice, theoretically this gap is bridged via simultaneous consultations with engineers and specialists. However, for many design problems this concurrency might not be achievable and applicable. In this paper, as one of the directions towards achieving this concurrency we specifically focus on the implementation of optimization techniques in structural design, to see how they can be integrated with parametric design techniques. To be more explicit from a computational design point of view, and to the design methodology itself, the focus of the article is on design information modeling, exchange and interoperability. The paper structure here onwards addresses questions and objectives, the process, the tool and the methodology. Subsequently, the results from the examples and a case study are briefly reported and eventually the discussion focuses on performative design methodology, its supporting design technology, rough Building Information Modeling (BIM) systems (Eastman et al., 2011) and future directions.

Question and Objectives

Two major questions are the subjects of exploration in this research. The first one, which is more from a computational design perspective, questions the possibility to appropriately integrate optimization algorithms and procedures, -in our case, topology optimization, within a parametric design system. Pertaining to this question, the objective is to design a system with connected sub-procedures and feedbacks with appropriate methods for design information exchange and translation from different CAD and programming platforms (operating as design decision support) for performance driven design (in this case is a truss structural system). The concurrency and consistency in extracting, generating and structuring of geometric design information such as size, resolution, etc.- and non-geometric design information such as load conditions, Degree of Freedom (DOF), etc. will be discussed.

The second question is how to make the process of topology optimization more suitable for the scale of architectural design and what are the benefits of doing so? This method and in general Finite Element Analysis (FEA) have been widely used at the scale of industrial design for uni-body or monocoques structures like bike frames (Figures 1a and 1b). However

Figure 1
a: Topology optimization method for designing of bicycle [1], b: COLNAGO monocoque bike frame designed using FEA, c: FEA applied in designing of a tower [1], d: Casted free form concrete column by Arata Isosaki in Shanghai, e: Close-up of Eifel tower column with similar morphology with steel elements.

for the scale of a building, while we usually have building elements like bars, beams, columns and joints, directly using the discretized result of topology optimization might not be much applicable and might impose choosing in-site concrete casting (Figures1c and 1d). While in this research, we build on the assumption that it would be more relevant for designing a truss or frame structures, if we translate the finite geometry to a proper geometric system with nodes and bars (Figure 1e).

While to a certain extent the process is defined and developed as a generic design technology, the type of structural system is intentionally and precisely defined as a trussed beam or cantilever. Besides the developed algorithms, from a technical point of view, testing and developing of various methods for information exchange between software and platforms like Matlab, Rhinoceros, Grasshopper plus some of its add-on plug-ins and the needed structural analysis software shall also be elaborated.

DESIGN PROCESS AND METHODOLOGY

The process, as illustrated in the flowchart (Figure 2), is a set of sub-procedures -A to D- such that the output, input and procedures are systematically correlated. In each sub-procedure there are four kinds of modules, which are decisions or inputs (), processes (), outputs () and visualizations (). To make this technology-based design process an interactive, cyclic and performative one, the following aspects have been taken into consideration:

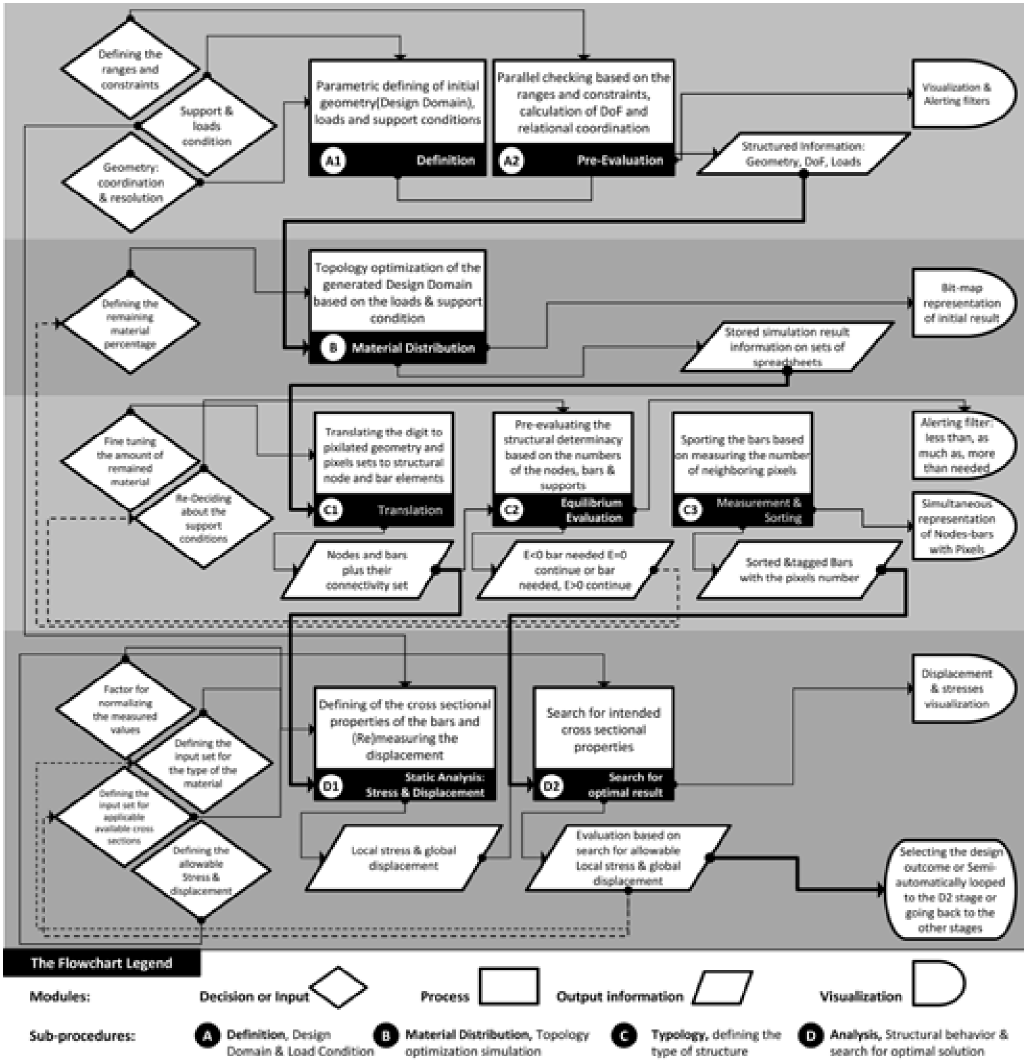


Figure 2
The flowchart of the process, illustrating the correlated sub procedures.

- The decision(s) or input(s) of each sub-procedure are used as common inputs for more than one of the sub-procedures, whenever and wherever needed.
- The final translated output in each of the sub-procedures would automatically or semi-automatically be processed as the input of the next sub-procedure(s).
- After each single measurement or evaluation module there is either a visualization for alerting or a feedback loop to the previous stages.

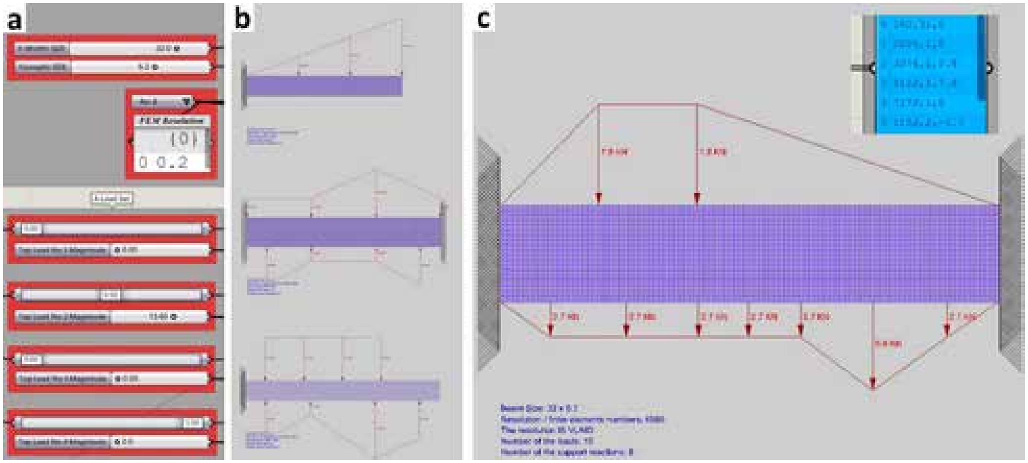


Figure 3
a: Some of the input parameters, b: Variations in design domain definition plus load and support conditions, c: A case with its corresponding output set.

The detailed descriptions of each of the sub-procedures are as follows:

Definition, design domain, discretization and load condition [A]

In this phase, the designer defines the geometrical properties on which the supports and loads can be parametrically added and modified. These properties are, so far, the span and the height of a cantilever or a beam with either upper or lower distributed or point loads on sides. However, the process in this stage and other stages is designed in a way that more irregular initial shapes are also possible to implement, by just removing some portions of the initial planar design domain. The main inputs in this sub-procedure are the dimensions, the magnitude and coordination of loads, supports and the mesh resolution (Figure 3a). Since this mesh resolution is indeed the discretization of the design domain for the following FEA, the acceptable resolution is a variable depending on the available computation time, power and the desired refinement. The output is a two-dimensional matrix or data list in *.txt* format that contains the relative dimensions of the geometry based on the discretization resolution, magnitude, the relative coordinates and calculated DOFs of each load positions based on the defined resolution. This step is done through visual programming using Grasshopper in Rhinoceros. The generated geometry attributes and alert messages (if either the geometry or resolution is not within some predefined range) are simultaneously visualized (Figure 3b and 3c).

Material distribution (MD); topology optimization [B]

In this stage, the goal is to find the optimal material distribution of the discretized generated design. This step is in Matlab and is based on the implementation and development of a topology optimization code, originally written by Sigmund (2001) with the purpose of solving linear compliance minimization using an optimizer and finite element subroutine. Modifications in the code are set up, with the objective of making it compatible with the input data files and supports interoperability of the output for the next sub-procedures.

The geometrical properties, DOFs and loads will be automatically called in the code and what has to be defined by the designer is the percentage of total remaining material. Consequently, two parallel results are the outputs of this phase, one a set of images that in real-time illustrates the results of material distribution simulation and the other, a set of

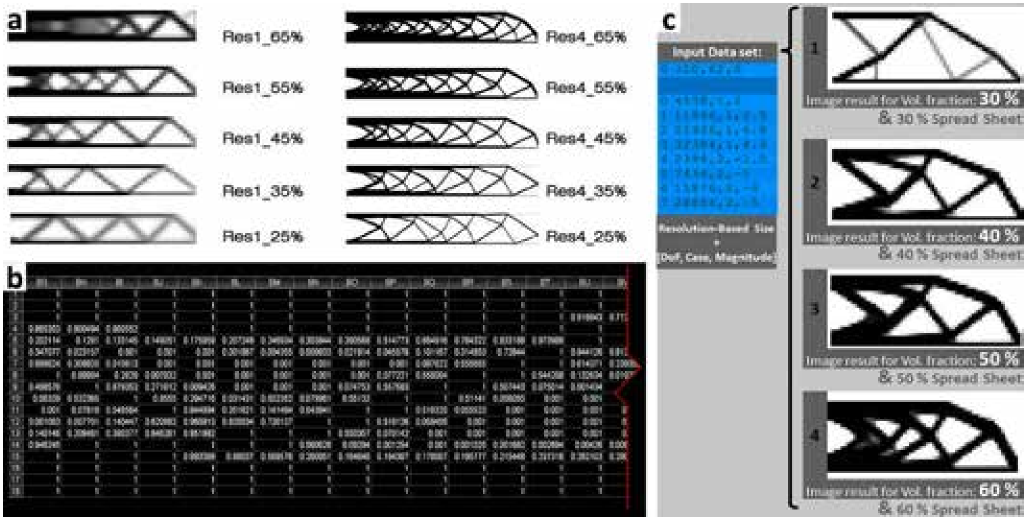


Figure 4
a: Tests for finding proper resolution ranges, b: Close-up of a result spread sheet with digits from 0 to 1, c: An input set example and four different topologies of the same design domain and load and support conditions.

excel spreadsheets, in which numerical values ranging from zero to one are stored. In the tested cases, four spreadsheets, respectively, with 30, 40, 50 and 60 percentage of remaining material have been the final outputs. In order to make this process more semi-automatic, further modifications can also be done in the code to pre-define the range for remaining material in previous sub-procedures (Figure 4).

Typology, defining the type of structure [C]

The goal in this sub-procedure is to translate discrete or pixelated geometry, which is the result information from the topology optimization to a vector-based geometric system with nodes and lines (Figures 5a and 5b). Although in the initial visualized topology the lines are detectable with the eyes of the designer, they are not automatically distinguishable for the CAD platform. So one of the main crucial challenges here was to extract the nodes and define the bars by using and developing appropriate algorithms in a way that the topologies do not change. This implies that if in a resultant image we see nine white polygons in the resultant vector geometry we should have also the same condition. Finally, the output is a matrix as *.txt* file with the required information of nodes, bars and load conditions in the desired format (Figure 5c).

Figure 6 illustrates the applied and developed

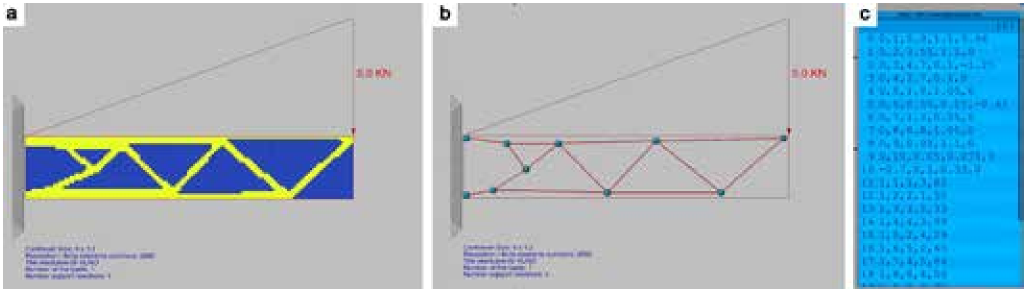


Figure 5
a: the converted spreadsheet to discrete geometry, b: extracted nodes and bars of same design domain, c: output set containing information on nodes, connectivity and load condition.

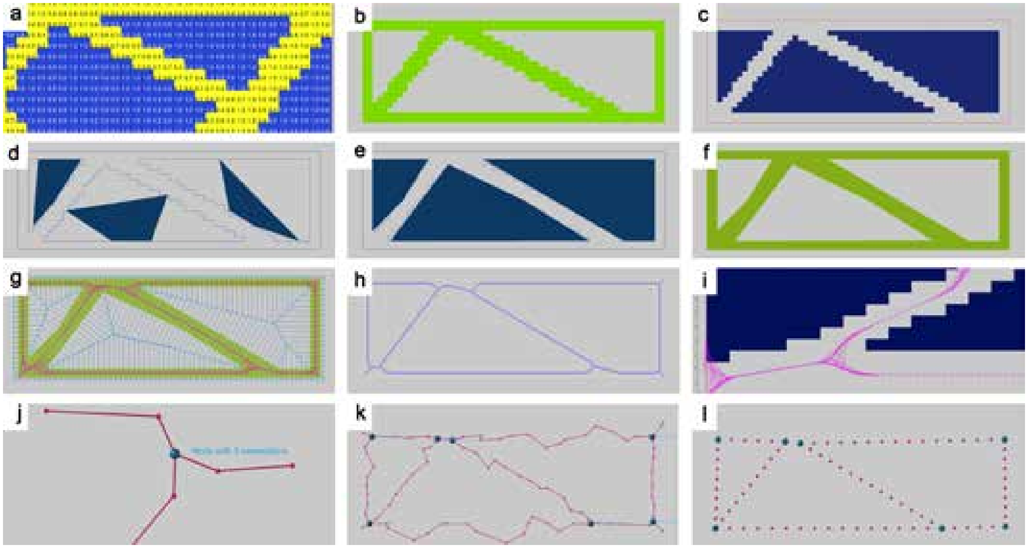


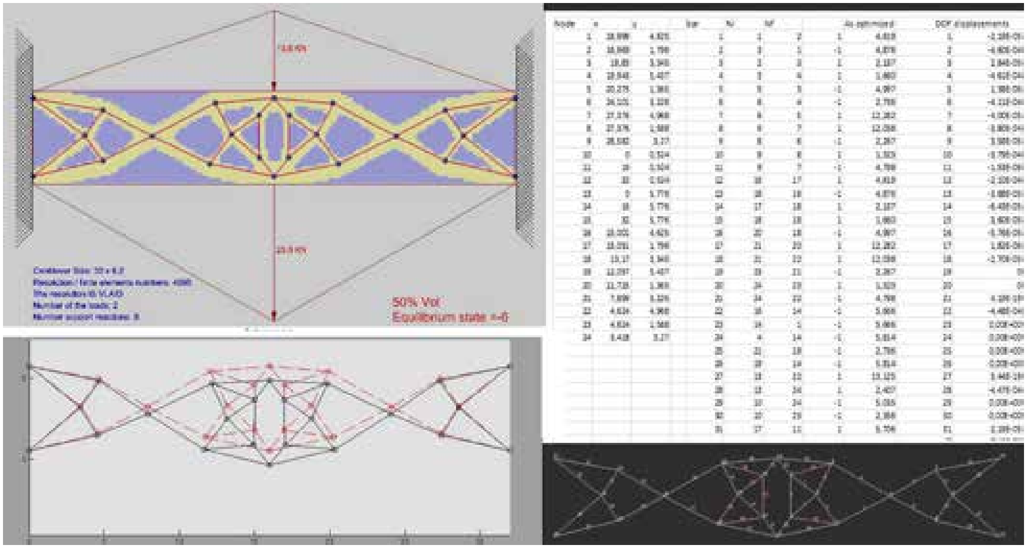
Figure 6
The methods implemented for translating discrete to vector-based geometry with nodes and bars.

methods for extracting the nodes from the resultant discrete geometry. After reading the float values on the spreadsheets and re-visualizing the results through using visual programming in Grasshopper, and tagging each cells with its corresponding zero to one value, a filter separates the cells into two lists of data. The reason for having this buffer is to let the designer find the appropriate continuous topology similar to the image result but this time composed of surfaces with the size of defined resolution. For instance, in the Figure 6 this filter value is 0.3, which means that all values less than this would be within a list to create the negative shape and those cells with values equal or more than this threshold will create the positive shape (Figures 6a-c).

In the next step, after joining the negative shapes and retrieving the outer boundary curves, the goal is to transform the jagged edges of these shapes into straight lines extract polygons. This is done through minimizing the difference between the areas of shapes with straight lines from the original one with jagged edges. (Figure 6d and 6e). This part is mainly done through visual and script based programming in Grasshopper, and Galapagos (evolutionary solver) for finding the shapes with optimum areas. By having the straight lines of the positive shapes (Figure 6f), it would also be possible to develop and apply a skeletonization technique based on Voronoi algorithms (Aurenhammer and Klein, 2000) to get axial curves with similar original topology (Figure 6g). Then by means of a Boolean gate the generated points through skeletonization algorithm can be achievable in a separate point cloud list (Figure 6h). After connecting the points to their neighboring, the nodes are those which has three or more connections. Therefore, another algorithm is developed to automatically detect nodes based on the numbers of connected neighbors (Figure 6i and 6j). Subsequent to this step another optional procedure is also developed in which the detected nodes would be anchor points of physical spring systems and other points will be stretched while having the fixed nodes as their supports. Therefore, with this method the poly-lines, which are not geometrically straight lines, will be stretched to form the bars.

Using this sub-procedure for all cases would allow us to have a persistent method to retrieve four

Figure 7
An overview of analysis for a beam case for one of the translated vector-based topologies.



set of nodes and bards for each of the volume fractions for any parametrically defined design domain with distinct load and support conditions in the first sub-procedure. After having the nodes and bars the structural determinacy of the each vector-based topologies will also be measured in advance through putting the numbers of the bars nodes and supports conditions in static equilibrium.

Analysis, structural behavior and search for optimal solution [D]

This stage starts with reading the input file in Matlab with the information on nodes, bars and load conditions from the previous step coming from the Rhino/Grasshopper. By having this information set for each of the four topologies, a static structural analysis will be run for obtaining local stresses and global displacement of the truss with the initial load and support conditions. Other variables such as material properties and available profiles can also be parametrically defined or extracted form a data set in this stage. Figure 7 presents an overview of this sub-procedure for a beam case. Here, the generated data list store the results that will be used for further visualization and profile assignation in 3D design environment. Further information for evaluation and comparisons for different input parameters and topologies like total volume, maximum and minimum length of the elements can be extracted from the optimum result depending on the design requirements.

The fitness criteria in the search process are allowable stress of the bars and global displacement. The search process finds the minimum required cross sectional area from the defined input sets for each of the bar elements and simultaneously checking the allowable global displacement. This part of the process is mainly done implementing a code in Matlab for cross sectional optimization. Moreover, in order to check the reliability of the process, some results have been compared with the results in the GSA suite. Figure 8 represents an overview for a cantilever that has started from the discrete geometry to vector geometry with nodes and lines in which the cross sectional optimization results are directly used as input data for tubular profile assignment, results in differentiation in the size of the each profile.

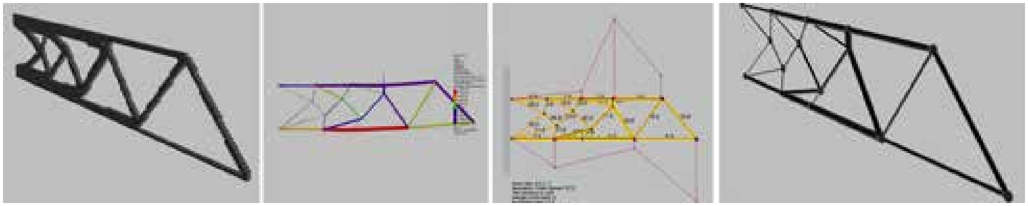


Figure 8
An overview of the last sub procedure with heterogeneous point load.

TESTS AND CASES

In addition to separate examinations inside each of the sub-procedures to improve and test the functionality and generalizability of the applied methods are conducted, two A-to-Z cases have been tested which will be briefly reported and shortly discussed here. First one is a cantilever case with one point load at its end (Figure 9). As it is illustrated here the results of optimization based on the initial design domain and load conditions are translated to a set of optimized truss structure. In this case and for any of its variation, besides the topological difference between the final topologies, the corresponding information sets pertaining to the structural performance and geometric properties of elements are also available for further evaluation and comparison.

The second case is a beam but in this case within a real world background design scenario for further validation of developed methods. This exercise builds upon a featured connecting bridges based project by Steven Hall Architects (Figure 10).

One of the benefits in this case is that there are similar design problems but with different sizes and proportions. This means that parametrically defining the initial design domain while having concurrent performance measurements would add to the efficiency of the design process itself. Additionally, as it is illustrated in Figure 10, for each design domain with different load conditions we have four optimized topologies in vector format with nodes and bars that can be translated to steel, wood or any other profiles. Moreover, based on cross sectional optimization we will have a differentiation in profile properties which might be a source of new performance driven design idea for designers. In other words, in addition to automatic evaluations and comparisons based on the generated and stored quantitative information, the developed design system might also suggest some implicit hints based on the visualized information and rough performance estimation. For instance in this case the architects might decide just to have one support for the roof of the bridge at a specific coordinate and have lateral beams to support the walking deck at

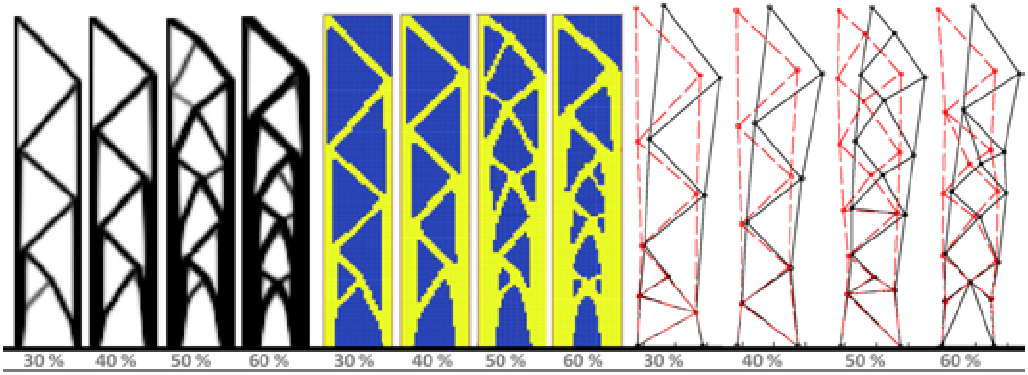


Figure 9
An overview of a tests on a cantilever case.

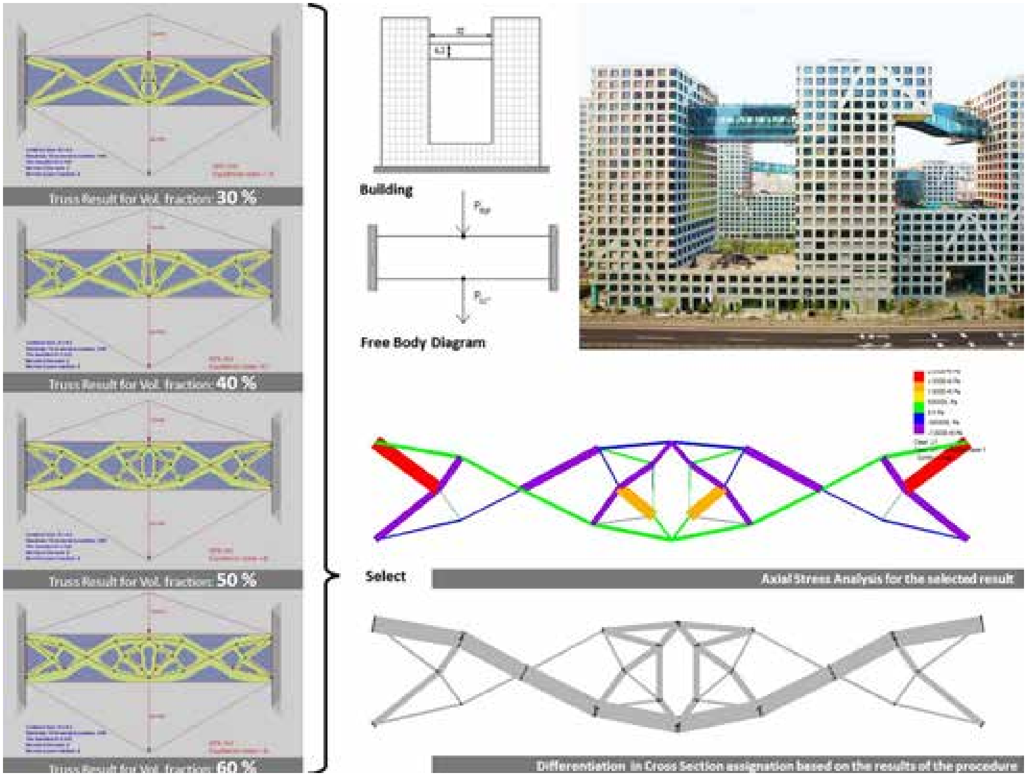


Figure 10
An overview of a case study to facilitate a performance driven design methodology for bridges in a project like linked hybrid by Steven Hall architects. Photo by [2].

every six meters. With these presumptions, based on what the designer perceived from the way the algorithms lead to optimum solutions, he or she could alter the input parameters, go back to the very beginning stages, and find the optimum result with required conditions and acceptable proportions simultaneously (Figure 11).

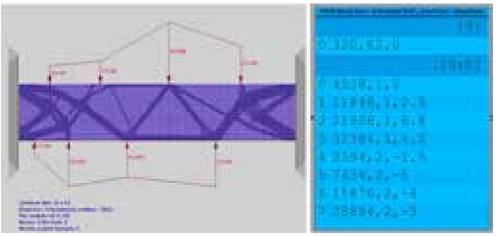


Figure 11
A feed-back attained through parametrically re-defining the initial conditions and the design domain for a similar case to retrieve another optimized topology plus needed geometric and non-geometric information for next stage.

DISCUSSION

In terms of design methodology, this research address the integration of performance measurement and evaluation modules in a parametric design system, opening the black box of topology optimization, making it more traceable, specific and applicable by designers, particularly at the scale of architectural design. Proposed algorithmic-design-information-exchange scenario between steps of the design procedure parallel to CAD and programming platforms have been considered and tested as an appropriate approach for this goal. Behind the benefits that can be implicitly and explicitly enumerated for this specific case, a conclusion is that knowledge integration in parametric design needs customized scenarios for integration and structuring of geometric and non-geometric information. The extent till which extraction and visualization of this information is needed, is dependent on one hand on the knowledge of the user as designer, and on the other hand on the design requirements and goals for a specific design problem.

From a design technology point of view, in addition to developed algorithms for solving the issues on interoperability or data exchange, what was peculiarly challenging in this research was developing and customizing a method for translating finite or discrete geometry to vector based and continuous topology. It is possible to deduce that the translation procedure can be considered as a more generic issue in parametric and performative driven design strategies. In addition to the process of FEA-based topology optimization methods in the realm of structural design, FEA methods are omnipresent in the basis of many simulation techniques. Considering this fact, it might be beneficial to facilitate performance driven design methodologies with methods, tools and strategies for such translational procedures. The implementation of skeletonization and node finding methods can be considered as some of these cases for such translational algorithms. Future cases need to be defined with similar methodological schemes to test their generalizability and functionality.

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[1] http://paulino.cee.illinois.edu/

[2] http://robertacucchiaro.files.wordpress.com/2011/12/146946-050-c6899f9f.jpg

Performance Based Pavilion Design

A dialogue between environmental and structural performance

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Abstract. *This paper investigates the design process of a performance based pavilion from concept towards construction phases, by challenging conventional form and fabrication techniques. The proposed project is considered as a temporary structure, located in Antalya, Turkey. A free-form structure and a parametrically defined cladding are designed to serve as an installation unit, a shading element and urban furniture. The pavilion geometry, performance assessments and proposed fabrication schemes are clearly described in the paper. The method integrates form, performance, material and fabrication constraints and exposes how environmental and structural performances, including Solar Access Analysis and Static Structural Analysis, may inform the design project.*
Keywords. *Parametric design; performance; architectural geometry; material; fabrication.*

INTRODUCTION

Design process consists of various phases from conceptualization to construction, including structuring of the problem, preliminary design, refinement and detailing (Goel 1992). Towards manufacturing of architectural form, different parties are involved in the design process, including the design and consultant teams. Architectural geometry needs to incorporate many requirements of aesthetic, programmatic, functional, technical and environmental aspects (Holzer and Downing, 2008). However, performance simulation of buildings is mostly undertaken in a later stage and cannot be integrated into design-decision making (Schlueter and Thesseling, 2009). This issue reduces the efficiency in the design process radically.

There are methods and tools developed for architectural design process, which investigate form, performance and material aspects of design. The rationalization process of free-form surfaces towards fabrication is widely investigated along with panelization tools, in which architectural geometry is subdivided into smaller components. The number of unsolved tasks is enlarged by the number of different materials being used, because their performance and manufacturing technology have to enter the panel layout computation (Pottman et. al. 2008). The statics-aware initialization procedure for the layout of planar quadrilateral meshes is approximated a given free-form surface, by obtaining the mechanical properties of the initial mesh (Schiftner and Balzer, 2010). A recent study aims to explore fundamental principles of a system, in which a performance based architectural geometry is generated. Parametric modeling, panelization tools and series of analysis tools are used with the intent of assigning different materials to the geometry within the same boundary conditions and comparing their structural performance results (Yazici and Tanacan, 2012). An integral computational model promotes an understanding of material, form and performance not as separate elements, but rather as complex interrelations (Hensel and Menges, 2008). As a similar approach, a research project investigated the possibilities and limitations of informing a robotically manufactured system with principles derived from biological structures (Krieg et al., 2011). In parallel to the projects fabricated, a recent research offered a software model, in which material, form, structural performance and manufacturing constraints are integrated into one system (Yazici, 2013).

Although the methods and tools mentioned are important in terms of incorporating various design issues, a holistic approach is necessary in order to integrate multi-performance requirements to the early stage of the design process. Different performance types, such as structural or environmental performance, require different issues to be considered in the design process.

In this paper, a performance based pavilion design is investigated as a case study. The intent is to create an integrated approach of which form, performance, material and fabrication constraints inform each other. By assessing structural and environmental performances of the pavilion, a free-form surface structure, along with a parametrically defined cladding is designed.

METHODOLOGY

The applied methods and constraints which influence the design process are identified. First of all, the pavilion geometry is clearly described in terms of its Non-Uniform Rational Basis Spline (NURBS) properties. Following this, performance assessments, including Solar Access Analysis and Static Structural Analysis, are explored by observing their influence to the overall geometry. Finally, possible fabrication schemes are investigated specified as steel and wooden structural systems.

The Description of the Pavilion Geometry

The pavilion is created by a combination of constraints related to the geometry, performance, material and fabrication techniques. A free-form NURBS surface is generated, which defines a 3D space specified by two major construction curves.

One of the construction curves is the *cross section rail* of the geometry. This curve is generated as a free-form profile. The idea is to generate both urban furniture as a sitting element and a semi-enclosed space, which may be organized as an installation unit and shading element. In order to accommodate these requirements, the profile defines two major curvatures, which define the section of the sitting element with h=0.58 m and section of the semi-enclosed space with h=3.32 m. The profile is designed to solve both of these requirements in a seamless and continuous way.

The other construction curve is a piece of a circle which works as a *rail*. The rail and cross section rail are used to generate the NURBS surface by using Sweep 1 tool in Rhinoceros software. The rail can be selected as a portion of a global circle with r=14.70 m, based on the needs and space available in the environment to construct the pavilion. Pavilion space can be increased or decreased by using same principles of the design and construction. This way of construction is particularly preferred compared to an already completed geometrical composition, in order to maintain flexibility in use of this temporary structure. Various scenarios can be implemented for the pavilion, which may enrich spatial experiences of the users.

The pavilion is considered as a small to mid-scale installation unit and the suitable portion of the global circle used for the pavilion is 50 deg. The geometry is generated free-form style by using 20 control points. The approximate dimensions of the unit are 9.00 m*8.20 m*4.02 m, which is considered sufficient enough to be used for an art installation (Figure 1).

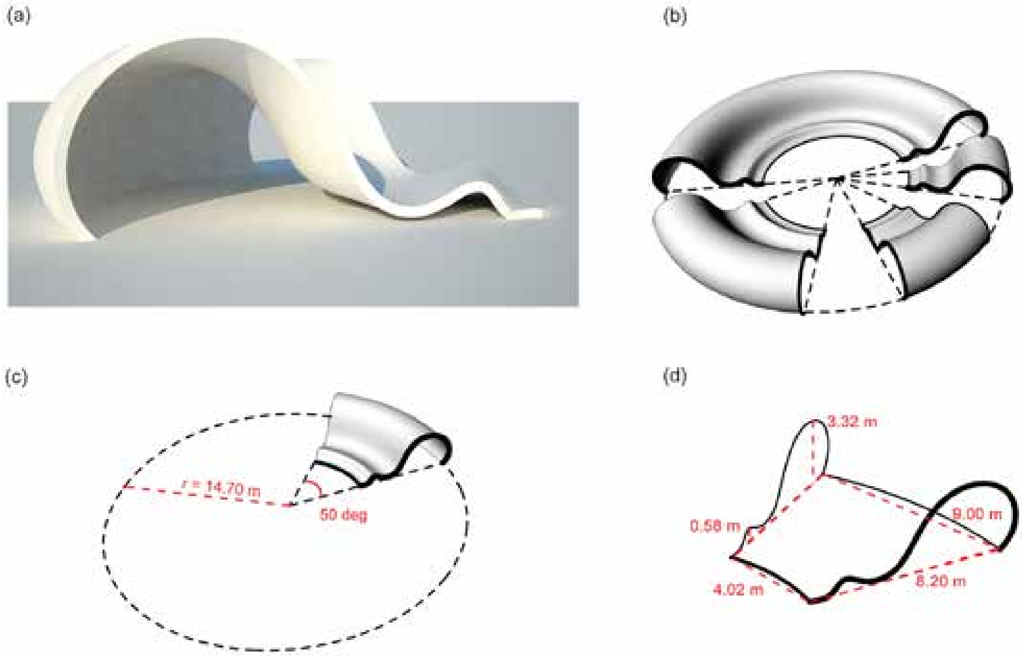

Figure 1
(a) Free-form geometry of the pavilion. (b) The overall geometry is a piece of a global circle which can be increased or decreased based on spatial requirements. (c) The selected piece which is considered sufficient enough for an art installation. (d) Geometrical description of the pavilion.

Performance Assessments through Static Structural Analysis and Solar Access Analysis

The proposed pavilion is located in Antalya Turkey. Antalya has a typical Mediterranean climate, which is characterized by warm to hot dry summers and mild to cold wet winters. Because of this reason, the pavilion has the task of being used as a shading element. Although the pavilion does not obtain a specific site in the city, it is considered be to be installed in north-south or northwest-southeast axes to eliminate the undesirable effect of the sun radiation, through the design of its cladding.

Following generation of the initial form, Solar Access Analysis is operated by Autodesk Ecotect, in order to evaluate the total radiation values affecting the geometry. Solar access analysis indicates incident solar radiation on the surface. The radiation calculations use direct or diffuse radiation data from the *weather file* of the city of Antalya, specified for the time period from September to October. The geometry is converted into a mesh, which consists of 1500 objects, in order to undertake the calculations. The orientation and tilt angles of individual objects are identified. Based on the relationship between the positioning of one piece and the angle of the sun light, the radiation value of that particular piece is calculated. Thus, the relationship of the objects and the sunlight can be established. The total radiation values ranges from 102992.422 to 871177.938 Wh / m2 (Watt hour/ per square meter) (Table 1). Through the solar access analysis, it is identified that the surface pieces which are almost vertical, which works as a wall, obtain higher radiation values compared to the other pieces. Reducing the area of surfaces closer to verticality is an important parameter in design of the pavilion. The cross section rail of the geometry is slightly adjusted through its control points to accommodate a better solution for the solar access analysis. Therefore, free-form geometry

Solar Access Analysis	Object	Orient.	Tilt	Total Radiation	Total Direct Radiation	Total Diffuse Radiation
ID	Type	(°)	(°)	Wh/m2	Wh/m2	Wh/m2
0000	Wall	-53.32	22.96	750727.000	402232.625	348494.375
0001	Wall	-54.11	25.96	791037.375	429239.906	361797.500
0002	Wall	-55.05	25.01	804416.250	447105.438	357310.781
0003	Wall	-51.04	20.83	703201.875	363437.031	339764.844
0004	Wall	-52.09	23.02	742622.312	394182.375	348439.938
0005	Wall	-52.53	22.57	755208.000	406380.375	348827.594
0006	Wall	-48.36	19.40	679358.250	343629.219	335729.062
...						
0739	Floor	84.37	-62.79	110386.078	230.860	110155.219
0740	Floor	-171.70	-69.03	107279.023	52.300	107226.727
0741	Floor	-174.91	-67.07	106750.359	200.100	106550.258
0742	**Floor**	**-174.07**	**-72.46**	**102992.422**	**0.000**	**102992.422**
0743	Floor	-176.76	-70.85	107836.070	34.500	107801.570
0744	Floor	-179.47	-75.72	103816.391	0.000	103816.391
...						
1481	Wall	-53.18	28.27	824098.125	453647.031	370451.094
1482	Wall	-54.10	28.76	832552.625	457229.000	375323.656
1483	Wall	-54.97	28.07	818652.500	448040.781	370611.719
1484	**Wall**	**-55.73**	**31.58**	**871177.938**	**487550.969**	**383626.969**
1485	Wall	-27.17	33.95	747919.875	350308.875	397611.031
1486	Wall	-54.55	28.96	842044.625	466881.312	375163.344
...						

Table 1
Solar access analysis representing attributes of the objects. The minimum and maximum total radiations are identified.

obtain the advantage of responding to the performance issues related to the solar access analysis better, as well as to the design issues by working both as an urban furniture and a semi-enclosed space.

In order to assess the structural performance of the geometry, Static Structural Analysis by FEM is undertaken with the Scan & Solve plug-in for Rhino. The plug-in works with NURBS surfaces without the need for converting the geometry into a mesh, unlike many other software used for the FEM analysis. Following the assignment of material to the geometry; boundary conditions and loadings are imposed. Numerical stress values and total deformations on the geometry can be identified, by using different materials and altering the geometry. By running the simulation for various scenarios; the geometry can be to be adjusted based on performance requirements.

Comprehensive boundary conditions would have a significant impact on the simulation, such as considering the impact of earthquake in the region. However, the fact that the pavilion is designed to be a temporary and preferably a lightweight structure, only the self-weight of the structure is taken into consideration for the analysis, in order to reduce the time of computation and simplify the simulation. By the FEM analysis, the problem areas on the geometry are identified. Although using different materials such as stainless steel or aluminum would influence the numerical stress values of the simulation, because the boundary conditions are less complicated, in which the geometry is rigidly fixed in three positions to the ground, the geometrical properties obtain the most important role to accommodate the structural performance requirements. Especially, the larger curvature which defines the semi-enclosed

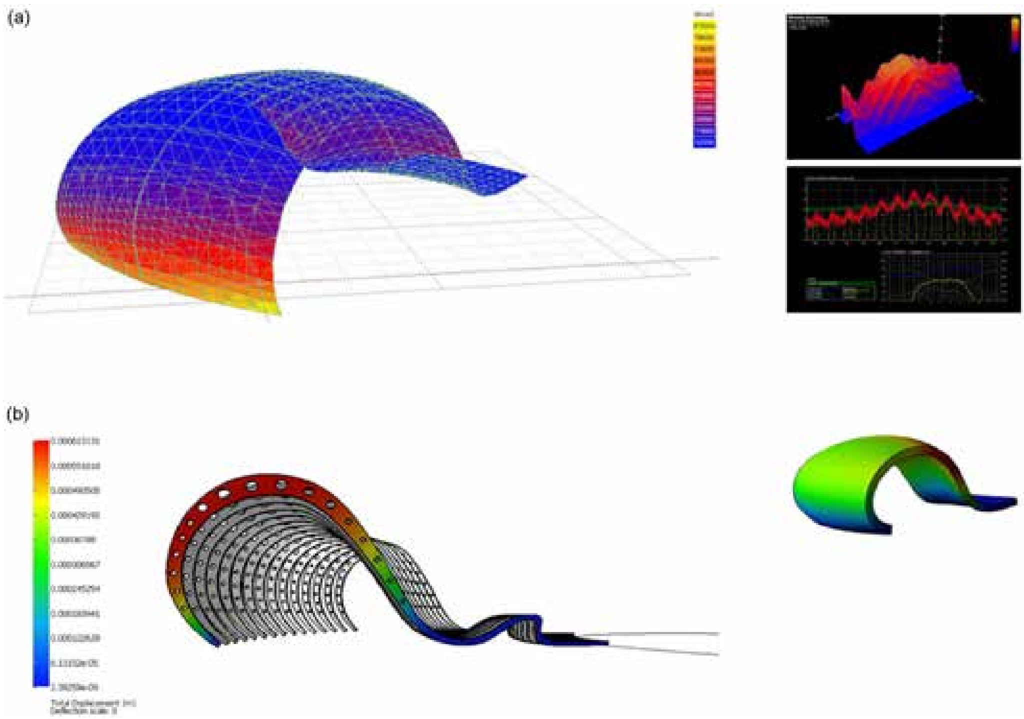

Figure 2
(a) Solar access analysis undertaken for the initial study of the free-from surface, by specifying the weather data of Antalya. (b) FEM analysis is undertaken for different geometry options by specifying material, boundary conditions and loadings.

space plays the critical role for the overall form with its height exceeding 3.00 m and span of approximately 5.40 m.

In order to generate the semi-enclosed space, a symmetrical geometry, which can be constructed by two rail curves, is selected for this study. If there is no symmetry; the structure would be unstable, require comprehensive structural solutions and additional structural issues may need to be addressed in the design process, which are considered against the design intent. If the section of the semi-enclosed space is closer to a circle, then the stresses on the geometry are equally distributed. By modifying the cross section rail of the geometry through its control points, the numerical stress values can be adjusted. Altering the geometry has also a significant impact on the panel layouts of the cladding, in terms of the panel sizes and numbers

One of the proposed structural elements obtains varied thicknesses in profile ranges from 0.07 m to 0.40 m in order to increase the strength of the structure on the necessary parts, such as the larger curvature which defines the semi-enclosed space. Additionally, in order to obtain a lightweight structure, the sections of these structural elements are enhanced by introducing holes in them (Figure 2).

Fabrication Scheme of the Pavilion

Because the pavilion is a temporary structure, pavilion pieces are designed to be easily demountable and light. Geometrical description of form is clearly identified for the fabrication purposes. In terms of constraints related to the transportation and assembly, structural elements are considered to be fabricated in pieces. Because of this reason, two material systems are tested for the structure; as steel and wood. These structural systems are compared in terms of their performances, as well as their lightness.

One of the options is using steel profiles for the structure, which is feasible in terms of achieving a lightweight structural system. Steel tubes are proposed to be bended according to curvature specified in the NURBS geometry. The diameter of the circular cross section of major structural elements is d=10 cm. There are 9 steel tubes which work as major structural elements, positioned according to the V curves of the NURBS surface. The spacing between these tubes ranges from 70 cm to 176 cm based on the V curves. Additionally, 21 horizontal steel tubes with d=5 cm are used to bind the major structural elements by following the U curves of the NURBS surface. The spacing between these tubes ranges from 59 cm to 65 cm based on the U curves. Material proposed for the cladding of steel structure option is opaque, acrylic glass with thickness of 3 mm. The idea is to use flat panels for cladding and mount them to the curvilinear surfaces. The acrylic pieces are considered to be fabricated by laser cutting machine, of which size is 80 cm * 60 cm. It is critical how to attach the flat panels to the structure. Therefore, a particular detail is developed in which the components are assembled in groups and then mounted to the structural elements which define the surface curvature.

The other option is using wood as the structure, which is considered to be manufactured by the Computer Numerical Controlled (CNC) machine. The fact that a complex geometry can be generated with a number of differentiated and highly articulated components by digital fabrication tools, the geometry is developed further to accommodate the fabrication constraints. The use of digital fabrication is preferably selected, because of reducing the waste material and obtaining advantages for a more sustainable design solution. The CNC machine available is able to handle maximum sizes of 200 cm * 400 cm wood sheets, with standard of 5 cm material thickness. The micro laminated wood is proposed because of its strength for a structural system. The number of major structural elements is 15, used with holes in the sections to reduce weight of the elements. The spacing between these elements is dense, ranging from 40 cm to 92 cm, because their thicknesses are considered very slim. There are also horizontal wooden binding elements, being implemented with the same principles as in the steel structure. Because of the constraints related to the machine, structural elements are proposed to be produced in pieces. The cladding of the wooden structure is 2D CNC cut plywood sheets with thickness of 3 mm, which can be used both flat or curved, because they are flexible to be bended to accommodate curvature on the surface. The maximum sheet size of the machine, which can handle sensitive tasks such as highly curvilinear surfaces, is 180 cm * 300 cm.

Although the structural elements made out of steel obtain the advantage of being lightweight, the fact that bending procedure of steel tubes reflects the quality manual operation, the precision to the 3D geometry may be problematic. The wooden structure has the advantage of fabricated with a small tolerance by the use of CNC machine. However, the weight of the wooden structure can cause problems. Additionally, because the structural elements made out of wood are considered to be fabricated in pieces, the assembly of the pieces can be challenging as well, by maintaining its structural strength. As a result, both options obtain advantages and disadvantages to be considered for the fabrication.

In order to create cladding, the NURBS surface is converted into panels by using a parametric definition at the Rhino Grasshopper. The opacity of the cladding is driven through series of design concerns and through the intent of controlling the sunlight. A gradient of surface opacity is generated to control sun radiation. It is possible to identify specific ratios between the opaque and/or transparent areas of the cladding and total surface area, towards finding the optimal solution based on climatic conditions of Antalya. First of all, the surface is subdivided based on UV curves on the surface. Following the genera-

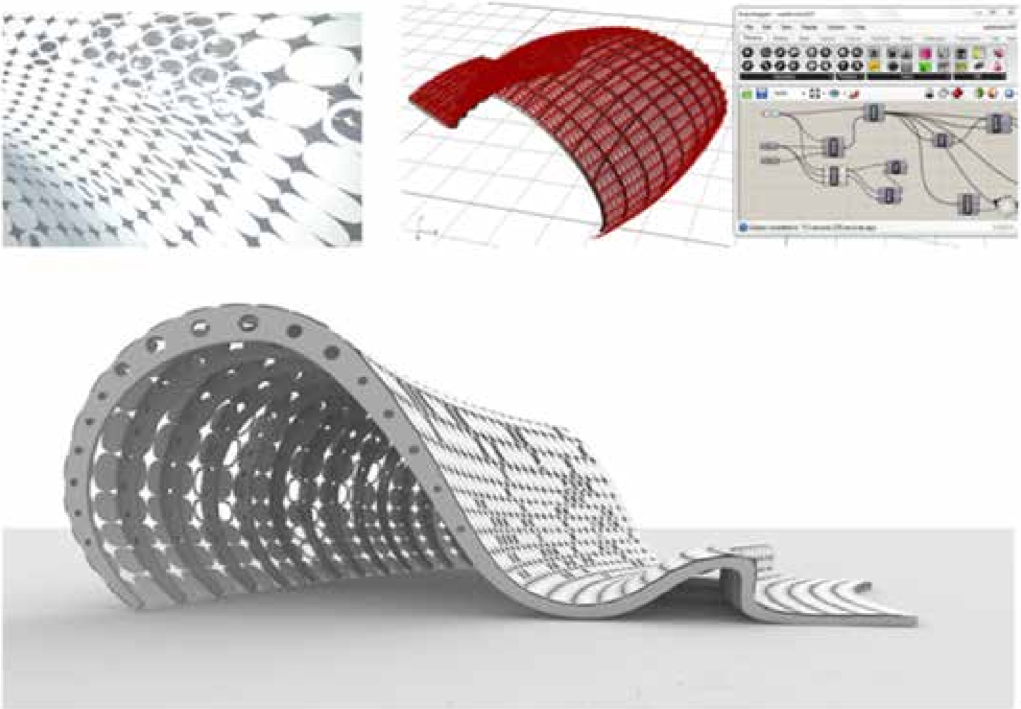

Figure 3
The panel layout of the pavilion is generated parametrically by considering the performance requirements.

tion of individual pieces by UV parameter, the surfaces are exploded. The extracted points are evaluated and used for regeneration of the panels. The panels should be unrolled to be fabricated in 2D by laser cutting or CNC machine. The panel sizes range from 23 cm to 52 cm and the total number of panels are 2000, based on the design intent. A relatively denser pattern increases the number of panels by alteration of the U-V curves of the surface. Although, various panel shapes such as quadrilateral, triangular or curvilinear panels can be created via the definition, curvilinear panels are selected and developed for the pavilion, due to its possibility for creating better design solutions for the opaque and transparent areas of the cladding. The panels should obtain flexible connections to allow movements. The connection elements are introduced in four sides of each panel. Because the panels are considered as non-structural parts, they are designed to be mounted on feasible positions of the actual pavilion structure (Figure 3).

RESULTS AND EVALUATION

The proposed method of the performance based pavilion design exposes how different performance requirements can influence a design project. The solar access analysis has proven that there is a direct relationship between the geometry and the solar radiation. For the given free-form surface, the vertical surfaces gain the most of the sun radiation for the time period from September to October for Antalya. Therefore, the geometry needs to be slightly altered to reduce those affected areas. Working with a free-form NURBS surface enables to modify the geometry through its control points, by maintaining its coherence and continuity. In addition to the solar access analysis, static structural analysis by FEM has indicated the importance of developing the geometry though the requirements of structural performance. The curvature, which defines the semi-enclosed space, plays the most important role due to the proportions of its height and span. In order to work as an installation unit, shading element and urban furniture, the surface profile needs to be continuous and fixed from at least three points to the ground for being stable.

The pavilion geometry can be enlarged or shrank, by adjusting the rail curve which is a part of a larger circle. This possibility brings also a systematic approach towards the construction of the pavilion. Additionally, the panels of the cladding can be informed by the climatic requirements, thus their opacity and transparency can be increased or decreased though the environmental data and solar radiation analysis. Therefore, the proposed pavilion accommodates requirements related to the both formal and performance issues.

Although, the proposed method integrates issues of the free-form pavilion from design towards construction, additional limitations may be confronted during its implementation.

SUMMARY AND CONCLUSIONS

In general practice, performance assessments of a design are usually undertaken in a later stage of the design process, as an engineering input which influences design radically and reduces the efficiency in the design process. In order to integrate formal and performance issues in an early stage, the design process of a temporary pavilion is identified. The aim is challenging the conventional form and fabrication techniques. A free-form NURBS surface is created as an installation unit, shading element and urban furniture, located in Antalya, Turkey. Two structural systems, as steel and wood, are investigated in order to accommodate the design requirements of the pavilion project. Structural performance and environmental performance assessments, including Solar Access Analysis and Static Structural Analysis undertaken by FEM, are operated in order to inform the geometry. The cladding scheme is generated via a GH definition, by designing opaque and transparent areas on the surface. The proposed method in this paper integrates form, performance, material and fabrication constraints. It exposes how structural and environmental performances may inform a design project.

The intent for the future work is to study the integration of various performance requirements with architectural form further. A model may integrate different types of performance requirements, form, material and fabrication techniques into one parametric system, where they are equally important and inform each other. This would increase efficiency in the architectural design process radically.

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Engineering Performance Simulations in Architectural Design Conception

Atrium in Shenyang: a case study on thermal mass

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Abstract. *The paper tackles the integration of engineering performance simulations in the conceptual phase of architectural design, with specific focus on parametric design processes. A general framework is exemplified, in which the use of performance simulations and the learning process of the designer are discussed in relation to the parameterization process. A specific case study is presented more in details regarding the design of an atrium for the reuse of an existing building in Shenyang-China. Performance simulations concerning the thermal comfort in the atrium are presented and discussed in relation to the general framework.*
Keywords. *Conceptual design; building simulation tools.*

INTRODUCTION

Since the requirements on the actual performance of buildings are becoming ever tighter, accurate data regarding the performance of the buildings is becoming increasingly important in the early phases of design. This paper tackles the role of digital modelling and engineering performance simulations in the conceptual phase of architectural design. The first part of the paper focuses on a theoretical framework for performance oriented parametric design, in which the design process is decomposed into and related to the design knowledge available during the design conception and its parameterization process; moreover, this part describes some general case studies. The second part of the paper grounds and exemplifies the framework, by discussing one specific case study on numerically assessed design alternatives for achieving indoor thermal comfort. The analysis of alternative design solutions is presented by showing the learning process of the designer through a comparative study. One chosen alternative is then presented in details, by undertaking the integration of parametric modeling and performance simulations during the design process. The parameterization process of the design concept is discussed based on the analysis previously illustrated; focusing on design innovation, emphasis is given to the importance of extracting knowledge from the numeric analysis.

DESIGN PROCESSES TOWARDS INNOVATIVE DESIGN SOLUTIONS

Background theories

Design processes towards innovative design solutions have been tackled and theorized from a number of different perspectives. Geoffrey Broadbent (1969) refers to four types of design methods, which he calls pragmatic, iconic, analogical and canonic. Pragmatic design makes use of available techniques without relevant innovation; iconic design recalls existent solutions and tends to replicate them; canonic design relies on rules and regulations as guidelines; analogical design makes use of analogies with other fields to define new ways for structuring the problems and their solutions. While all these four methods can be used to generate design alternatives by exploring various concepts, it is especially the last one that allows for major innovation. It is widely acknowledged that looking for innovative solutions for new design concepts deeply relies not only on the previous experience of the designer, but also on his/her real time learning process. The importance of prestructures, presuppositions or protomodels as the origins of solution concepts (Roozenburg and Cross, 1991) is recognized, but leads to an evolving design path in which the learning process is an integral part of the exploratory design activity. In a puzzle-making approach (Alexander et al., 1977), designers begin with a kit of forms, including materials and shape, subject to modification according to certain rules until they achieve some desired functional qualities; inductive reasoning is used with the aid of metaphors, symbols, and case studies (Kalay, 1999). Analogical reasoning implies learning from previous or other problems similar to the actual problem by retrieving and transferring chains of reasoning and knowledge to the actual problem (Veloso, 1994); it is quite beneficial to problem solving processes including design (Goldschmidt, 2001; Goldschmidt and Smolkov, 2006). A number of design methods are based on abduction (Tomiyama et al., 2003), using logic and abductive reasoning; according to this, a design solution is defined by means of axioms and theorems, respectively intended as design knowledge and properties of other design solutions. Specifically, following Roozenberg's (1993) distinction, 'abduction' in design theory and knowledge-based design systems is explanatory abduction while the reasoning towards new solutions for design problems follows the pattern of innovative abduction.

Integration of engineering disciplines and Performance Simulation Tools

Within the broadly theorized field described above, focus is given here on the integration of engineering disciplines in the conceptual phase of architectural design. Their use to trigger the design creativity is approached in opposition to post-engineering processes. In traditional post-engineering processes, technical performances are mostly considered and verified in late stages; the design variations eventually necessary to satisfy the technical requirements are tailored upon preconceived and constraining architectural designs. In contrast with this attitude, the use of engineering performances is proposed in order to inspire or even drive the concept improvements or the generation of new alternative concepts; this implies that engineering feedbacks are an integral part of the analogical method and a support for innovative abduction. Aiming at this, building Performance Simulation Tools and their use in the early phase of the design play a crucial role. This perspective is in line with a number of previous and well-known studies, such as the ones of Mahdavi and Lam (1991), according to whom systematic "front-end" studies based on digital simulations to aid preliminary design decisions should be preferred over the traditional approach, in which the role of building simulation is relegated to the "back-end" of the design process. The use of feedbacks from analysis software to re-evaluate design decisions is also emphasized by Caldas and Norford (2003), who point out that 'by using simulation tools, it is possible to engage in a design practice based on feedback loops between making design decisions and evaluating their environmental impact, as a way to inform the on-going process of design. However, the view proposed here differs from previous works due to its focus on the use of numeric design assessments as part of the learning process of the designer, to achieve innovative design solutions.

Design knowledge acquisition in parametric design

In a previous publication, the authors proposed a parametric design framework for performance-oriented design, in which the use of numeric design assessments are related to the learning process and knowledge available or generated during the design process. Three phases are distinguished in the parametric design development. During the first phase, strategy-definition, the parameterization is addressed based on the analysis of design challenges; during the second phase, model-building, the parametric model is constructed; during the third phase, solution-assessment, the design alternatives embedded into the parametric model are explored based on performance evaluations (Turrin et al., 2013). Numeric design assessments play a crucial role both in the first and in the third phase. According to this framework, three general types of processes are distinguished, in which the solution space of the parametric models is differently set. This usually occurs according to the knowledge the designer has or gains before or when defining the parameterization strategy, in respect to a set of selected performances. The first includes design processes in which little knowledge is available during the parameterization process, with consequent need of enlarging the design solution space for broad performance explorations. This leads to large parametric solutions spaces; and usually implies intense use of numeric assessments in the solution-assessment phase. The second includes design processes in which relevant knowledge is available during the parameterization process, with consequent chance of bounding the solution space into a more confined collection of alternative design solutions. This leads to narrowed parametric solution spaces; and, unless knowledge is already available, it implies some use of numeric assessment both in the strategy-definition and solution-assessment phases. The third includes design processes in which a clear (mostly bijective) relation between geometry and performance can be set during the parameterization process; this allows consistently relating different geometric solutions with different performance requirements, which leads to bijectively deterministic parametric solution spaces; and, unless knowledge is already available, it implies intense use of numeric assessments in the strategy-definition phase. A substantial difference across the three cases consists of the way in which the initial design concept (here named primary generator according to Darke, 1979) is conceived in relation to the considered performances. Numeric design assessments are considered a means for extracting knowledge to be used (or re-used) in the conception of (new) primary generators.

Four examples are mentioned here following; additional details can be found in previous publications. The first example (Turrin et al., 2013) concerns the design of an envelope controlling effects of direct and indirect daylight in the interior space; it was developed by a student (Friedhoff Calvo, 2010). The primary generator was developed based on Escher's tessellations, with intuitively defined modular variations from permeable to impermeable to daylight. In order to explore the daylight effects in alternative designs, the geometry of the primary generator was parameterized. Considering the intuitive nature of the design, the parameterization aimed at a broad solution space, to reduce the risk of excluding meaningful design alternatives. As a consequence, further computational support (i.e. search algorithms) was needed in combination with performance simulation tools during the solution-assessment. Focusing on the learning process of the designer, the use of search algorithms is addressed in the following example. The second example (Turrin et al., 2011) concerns the design of an envelope that reduces the solar gain but allows a high daylight level. The primary generator was developed based on well-known principles of shading and orientation, but applied on complex geometry. The geometry of the primary generator was parameterized in order to lead to a large solutions space; and a search for well performing solutions was performed based on a genetic algorithm optimization, in combination with performance simulation tools. The generated solutions were stored in a database and analyzed in order to extract information from badly performing, sub-optimal, and well performing solutions, aiming at an explicit understanding of trends between geometric design variables and resulting performances, toward design knowledge generation. The third example (Turrin et al., 2013) concerns the design of an envelope to control the daylight effect on the enclosed spaces; it was developed by a student for his M.Sc. graduation project (Van Kersbergen, 2011). The primary generator was developed only after an extensive number of preliminary performance simulations on different basic primary generators. The geometry of the chosen primary generator was parameterized based on the results of the previous analyses, in order to lead to a narrowed solutions space; and, during the solution-assessment, performance simulations were run only on chosen design alternatives. Based on the increased correspondence between the actual and desired solutions space, as it was expected, the chosen options showed performances quite close to the desired requirements. This attitude towards amplifying the learning process (by means of numeric assessments) before parameterizing and even conceiving the primary generator is shown in its extreme consequences in the fourth example. The fourth example concerns the design of an acoustic absorber which was developed by a student for her M.Sc. thesis (Setaki, 2012). Intensive work was invested in performance measurements of samples, which not only increased the design knowledge, but also formalized it. Only when a clear relation was formalized, the primary generator was conceived. A parametric model was made based on the formalized relation, in order to bijectively relate specific acoustic requirements with correspondent geometric design alternatives. So far, this case showed mostly full coincidence between the actual and the desired solution space of the parametric models.

With reference to this framework, the following section presents in detail one case study from a practice-based design process for an atrium. The performances considered in this project focus mainly on passive climatic control.

STUDIES FOR AN ATRIUM IN SHENYANG

The atrium is part of a larger project developed by GWS, a company located in Beijing. The project consists of the conversion of a tobacco factory into office buildings, organized in three blocks around a courtyard. The atrium is located in one of the three buildings, developed along an East-West axis, on the northern side of the plot. The building is organized in five floors and has a total volume of approximately 130.000 cubic meters. GWS developed a number of design alternatives, in most of which the atrium is located on the top two floors and occupies a volume of approximately 8.000 cubic meters. The spaces around the atrium are mainly offices or flexible areas, for which the atrium acts as a distribution space. The work presented in this paper is a part of the output of a collaboration between GWS in China and an interdisciplinary team at TUDelft, in the Netherlands. The collaboration assumed the general setting of the overall project as given, while focusing on the atrium and related roof. A number of design options were developed, by considering performances for passive climatic comfort and, in general, reduction of energy consumption during use.

The following sections present the preliminary numeric analyses run on the building, based on which challenges and potentials to reach the design goals were identified. Based on these results, specific sub-goals were established, which decompose the design requirements into more specific tasks.

Strategy-definition phase: preliminary performance simulations

Shenyang is located in the fifth level of Chinese climate zones, defined as "coolest level"; within this level, the area belongs to the class B, which corresponds to the most moderate class of the "coolest zone". According to the Shenyang IWEC weather statistics, the winter peak happens between December and February, with the coldest hour at 5am, typically below -10 degrees Celsius; the summer peak happens between June and August with temperatures generally above 25 degrees Celsius at 2pm.

The work presented in this paper focuses on thermal comfort, and specifically on passive measures for achieving thermal comfort; while considerations on daylight are taken into account as side criterion only. A number of preliminary numeric analyses were run on the given building, in order to identify expected problems and potentials for passive climate comfort. Simulations of thermal comfort based on Predicted Mean Vote (ASHRAE, 2010), and of air, mean radiant and operative temperatures were performed on the whole building for both a whole year, and with focus on periods in which worst conditions occur for risk of overheating (July) and coldness (January). Simulations were run both in free-running-mode (without mechanical heating and cooling) with no occupancy and no internal heat loads (in order to measure the effect of the building only, for passive thermal comfort); and by including HVAC systems, occupancy and internal heat loads. Design Builder (DesignBuilder Software Ltd) was selected as building performance simulation tool. Moreover, daylight conditions were studied for the floors where the atrium is included, at equinoxes and solstices, using Radiance via Diva for Rhino. Regarding the passive thermal comfort, digital simulations were systematically run on a set of different variations concerning several material properties of the external walls, roof and glazing (different levels of insulation); air tightness of the building; and thermal mass. Insulation levels (U-value) varied from 0.35 to 0.25 W/(m2·K) for the external walls, from 0.25 to 0.15 W/(m2·K) for the flat roof and from 1.978 to 1.415 W/(m2·K) for external glazing; air tightness varied from 0.7 to 0.2 ac/h; different thicknesses of the floor determined the thermal mass, in heavy concrete; some options were tested also with natural ventilation. The building was modeled based on its external envelope, subdivision into floors and atrium. The model consisted of 34 real and virtual thermal zones, 4 of which regarded the atrium; these latter are named 4a and 4b for bottom and top part of the atrium on the fourth floor; and 5a, 5b respectively on the fifth floor.

Results

The results showed that higher insulation results in higher indoor temperatures both in winter and in summer; and higher leakage implies lower indoor summer and winter temperatures. The effects of occupancy, internal heat loads, increased insulation and increased air tightness were expected to be beneficial in winter, and unfavorable in summer. Summer thermal comfort increased when including ventilation. Both for July and January (daily values), a comparison was also made in case of additional thermal mass distributed on the floors surrounding the atrium. The thermal zone corresponding to the bottom area of the atrium was obviously the one affected the most by the effect of thermal mass, since it lies on a floor, differently than the other three thermal zones. Some of the results are summarized in Table 1. In addition to the comparison between operative temperatures, relevant information was extracted also from the analyses of air and radiant temperatures; and from the behavior of the PMV, especially on the bottom thermal zone. In this zone, in case of little thermal mass, the PMV varied from 2.8 (2nd July) to 4.9 (18th July); in case of additional thermal mass, the PMV varied from 1.7 (4th July) to 3.9 (24th July), which clearly showed the delaying and peak-shaving effect of the thermal mass. Finally, a simulation was run adding the effect of thermal mass and natural ventilation (5 ac/h), showing additional benefits. As an example, in the bottom thermal zone the PMV varied from 0.3 (4th July) to 2.2 (18th July). Finally, a series of shadow analyses were made, which pointed out correspondence between solar gains and temperatures.

Conclusions and specific sub-goals

According to the preliminary analyses, the whole building and the atrium especially had critical thermal discomfort both in winter and in summer. The

U-value (W/(m2·K))			Air t. (ac/h)	Vent. (ac/h)	Th.M.	Min. Win. temp. (C°)		Max. Sum. temp. (C°)	
Wall	Roof	Glazing				4a	5b	4a	5b
0.35	0.25	1.978	0.7	0	No	-14.9	-24.1	36.4	50.3
0.25	0.15	1.415	0.7	0	No	-8.3	-21.4	41.9	53.0
0.35	0.25	1.978	0.2	0	No	-8.2	-21.1	42.0	53.3
0.25	0.15	1.415	0.2	0	No	-8.2	-21.0	42.0	53.3
0.25	0.15	1.415	0.2	5	No			33.8	46.8
0.25	0.15	1.415	0.2	10	No			33.7	45.7
0.25	0.15	1.415	0.2	0	Floors	-4.5	-20.4	38.8	53.0

Table 1
Minimum Winter and Maximum Summer operative temperatures (temp.) in variants for insulation (U-value), air tightness (Air t.), natural ventilation (Vent.), and additional thermal mass (Th.M.).

analyses showed also that it is possible to reduce thermal discomfort by means of passive strategies, both in summer and in winter. Specific sub-goals were identified. Considering the local climate, calibrating the design first based on the cold winter period was recommended. This clearly included increasing the insulation, air tightness and solar gain of the building as much as possible. However, this challenged summer thermal comfort. As also confirmed in the preliminary analyses, thermal mass and summer ventilation positively impacted summer comfort. Among these factors, the work illustrated in the following sections focuses on the distribution of thermal mass, natural ventilation and shading, since these factors highly depend (also) on the geometry of the overall spatial configuration of the atrium. Specifically, investigations on thermal mass were taken as starting point for the next phase of the strategy-definition phase, in which the parameterization strategy was more specifically addressed.

THERMAL MASS AS DESIGN DRIVER

The principles described above were investigated as design drivers, by making use of digital simulations to study their thermal behavior in conjunction with the design exploration of a large range of design possibilities. Especially when considering the dimensions of the atrium and its value as representative space for the new office building, conceiving such a thermal system with emphasis on its iconic value (in addition to its technical thermal function) was proposed as beneficial for the project. A relevant part of the strategy definition phase focused on thermal mass. The following sections summarize its main aspects.

Additional analysis on thermal mass

A set of additional analyses were carried out regarding the effects of quantity and distribution of thermal mass within the atrium. The effect of different distributions of additional thermal mass was analyzed for four vertical (virtual) thermal zones of the atrium, with and without natural ventilation and shading. Among the analyzed options, the one with external shading, diurnal and nocturnal ventilation (10ac/h), and higher concentration of thermal mass on the top part of the atrium showed the best performance for summer thermal comfort. The results are visible in table 1 and clearly show the accumulation of heat in the thermal mass and the cooling effect of ventilation, as well as the reduction of overheating through the addition of external shading on the glazed roof. Additional tests were run accentuating the uneven distribution of thermal mass across the levels. These analyses showed that additional thermal mass on the top level leads to beneficial effects, while changes in the bottom level had minor effects on the thermal performances. Since minimizing the use of additional material and structural load is generally desirable, the option of reducing the additional thermal mass on the bottom level and distributing it more on the top level was used for further investigations. External shading further reduced the maximum temperatures as can be seen from Table 2.

Table 2
Maximum summer operative temperatures of simulated variants for ventilation, shading and thermal mass distribution in the atrium.

ventilation	shading	thermal mass	Max. operative temperature (deg. C.)			
			4a	4b	5a	5b
no	no	no	42.0	43.5	48.5	53.4
no	no	floor 5b	41.8	43.2	47.8	48.1
no	no	floor 5a, b	41.6	45.4	57.2	49.7
no	no	floor 4b, 5a, b	41.6	49.2	57.4	49.9
no	no	floor 4a, b, 5a, b	41.6	50.3	59.6	51.0
10 ac/h	no	floor 4a, b, 5a, b	34.8	34.8	39.6	41.1
10 ac/h	yes	floor 4a, b, 5a, b	33.8	32.8	35.3	41.1
10 ac/h	yes	floor 4b, 5a, bx2,	34.3	32.5	34.8	38.3

Based on the preliminary analyses, geometric properties were extracted for the aspects having positive impact on the design goals; for different primary generators, the attributes of these geometric properties were parameterized in order to investigate geometric alternatives. Examples are provided in the following section.

Primary generator and parameterization process

Focusing on the satisfaction of the primary goal of the design at hand (namely the improvement of the thermal performance of the atrium), the numeric analyses described above enabled the quantification of a suitable distribution of thermal mass across the vertical levels of the atrium. This information allowed to identify a first numeric rule based on which geometric options were to be designed. Various primary generators and related parameterization processes were developed to explore different design directions responding to this rule. Within the boundaries of this rule, additional aspects were considered in order to enhance the thermal benefits and to include other criteria, such as structural performance and daylight. The primary generators were developed considering the thermal benefits of exposing the mass to winter solar radiation and protecting it from the summer one. Additionally, they were developed considering that the heat accumulated during the winter days from the atrium should be released toward the surrounding areas (back areas), which is where the thermal benefits are especially required. Based on a shadow analysis in Ecotect (Autodesk), the areas irradiated in summer were distributed along all the levels of the atrium on its north, east and west sides; while the areas of the atrium irradiated in winter were located on the north side of the top level of the atrium only. These latter areas were therefore chosen for distributing the thermal mass. The other criteria were addressed within the subdomains of this design space (detailed arrangement, form, material and construction of the system), based on the absence of significant degrees of conflict with the main objective (thermal performance). Among the explored directions, one is exemplified here following, in which a set of sliding panels was proposed for the atrium; this resulted in a set of vertical panels in concrete, anchored along the north side and the top part of the south side. In this design option, the effect of thermal mass was focused on the diurnal fluctuations, leading to an active thickness of 10 to 15 cm for concrete. Considering that at the back of a 5 cm thick concrete panel the fluctuation is 72% of the fluctuation at the front and at the back of a 10 cm panel it is 51%, the need of releasing heat toward the back areas was to be addressed. Instead of rotating the heavy panels, fixed panels were combined with sliding thermal insulation to prevent nocturnal release of accumulated heat toward the atrium; and to favor the thermal behavior at the back of the panels. Figure 1 illustrates the principle.

Given the suitable distribution of thermal mass across the vertical levels, the general layout of the panels was treated as a layout problem, in which the requirements for mass distribution may correspond to several panel layout solutions. A parametric model was established in order to investigate layout alternatives, both by decreasing the dimensions of the panels from the topmost to the lowermost part of the atrium, and by reducing the amount of panels in the same fashion. The latter scheme was preferred since it allowed for mostly uninhibited access to the atrium floor. In this option, the parameterization included the number and the dimensions of the panels (and therefore also affected their intervals), by generating a narrowed solution space. Figure 2 schematizes this option (and suggests possible alignment of the vertical panels with the structure of the roof).

A separate parametric process regarded the form of the panels. In this case, the parameterization aimed at a large solution space, later explored with the support of genetic algorithms during the solution-assessment phase. A number of requirements were specified with regard to thermal, functional and structural performance. Specifically, the total thermal mass should approximate the distribution that resulted from the thermal calculations and the panels of the topmost floors should be exposed as much as possible to the south, so as to receive adequate sun radiation during wintertime. Moreover, the form of the panels should be such as to allow for the sliding insulation panels to slide in front and behind the thermal masses. Finally, given that the panels covered the full height of the atrium and were anchored to the building structure in limited locations, efficient distribution of loads should be achieved, so as to minimize deflections resulting from their own weight as well as from occasional horizontal loads. A number of geometric properties affecting these requirements were parameterized; and a multi-objective optimization problem with three objectives and two constraints was formulated. The objectives were: the approximation of the calculated thermal mass distribution; the maximization of surface exposure to the south and the minimization of deflection under several load-cases. The constraints regarded the suitability of the shape for sliding panels and their curvature (for fabrication considerations). In the preliminary stage of the solution-assessment, the parametric model embedded finite element calculations (via Karamba3d), in order to obtain data about the stresses and displacements; simple geometrical operations were used to evaluate functional adequacy and exposure to solar radiation; and, a multi-objective genetic algorithm was used to search for non-dominated solutions. Given that the objective functions are conflicting, a set of non-dominated solutions was obtained. Selection among them was performed so that the selected one would perform adequately with respect

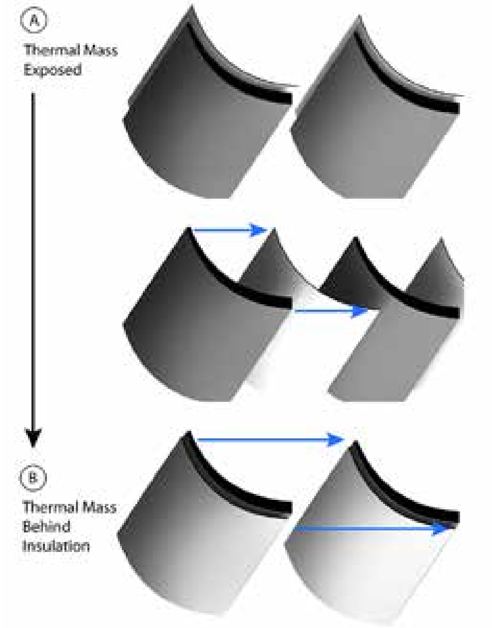

Figure 1
Combination of heavy panels and sliding insulation to enhance the back diurnal fluctuation in the thermal mass.

Figure 2
Layout of the vertical concrete panels (thermal mass).

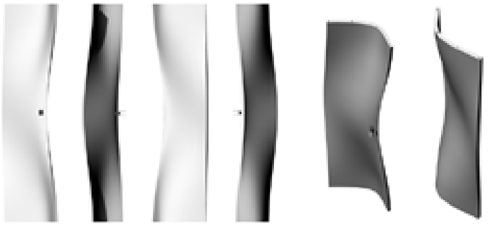

Figure 3
Example of curvature resulting from parametric studies of the concrete panel.

to all goals, as well as according to aesthetic preference. Figure 3 exemplifies the panels.

CONCLUSIONS

The paper presented the studies for an atrium in Shenyang, for which a number of design proposals were developed based on performance-oriented parametric investigations. The process was exemplified according to a parametric framework in which aspects affecting the thermal behavior of the atrium were discussed as design drivers. The process included an extensive number of performance simulations, whose role regarded both the strategy-definition phase and the solution-assessment phase. Larger emphasis was given to the strategy-definition phase, in order to highlight the relevance of preliminary knowledge. Additionally to this aspect, a conclusive remark is proposed on the crucial role played by performance simulations in enhancing the interdisciplinarity of the process, also by heightening the brainstorming across the various disciplines involved in the design process.

ACKNOWLEDGEMENTS

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Passive Energy Devices in Ceramics

A study in slip casting toward sweaty, scaly buildings

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Abstract. *Buildings with scales, buildings that sweat: this paper proposes two strategies for a materially grounded, performance-based architecture which leverages the strengths of computation and CNC fabrication against the basic properties of traditional ceramics.*
Keywords. *Building performance, CNC tooling, computer aided manufacture, ceramics, passive energy design*

TWO APPROACHES

Two prototypes for passive, energy saving devices involve the use of ceramics to create high performance building envelopes. One strategy uses the tendency of porous ceramic materials such as clay to wick moisture to the exterior of a building causing it to "sweat" and thus to cool itself passively in dry climates. A second strategy uses bi-colored ceramic "scales" to create an array of solar collector/diffusers which can be used to shuttle heat energy either into our out of a building. Both strategies take a cue from systems in nature to leverage a material-based strategy for thermoregulation in buildings. These devices are the result of computer modelling and CNC fabrication to mill positive forms for two types of plaster mold making for ceramic slip casting. One technique is industrial, using pressurized multi-part forms, while the other method uses traditional run-through slip casting molds.

The Sweaty Facade

The built environment as we know it is characterized by constructions which function to keep occupants warm and dry; rainwater is typically displaced from the building footprint and channeled away with gutters, swales, and ultimately retention or detention strategies. Recent popular attention to sustainable building has increased the use of cisterns to collect and reuse water, but these uses remain relegated to watering landscapes and flushing toilets. Biomimetic strategies, however, have been proposed to mimic beneficial cooling effects caused by sweating in mammals (Lilley, et al., 2012). Prototypes are underway for an envisioned "Sweaty Façade" which will use the natural osmotic characteristics of clay to allow buildings to sweat, thus taking advantage of the heat of evaporation of water to passively cool buildings in warm, dry climates. Water collected at the roof can be used to fill façade components which will sweat to save energy.

These intentionally wet façade modules will take forms characterized by highly textured or folding surfaces to create large surface areas for the evaporation of water. Using simple parametric repetition in Rhino/Grasshopper, along with Kangaroo

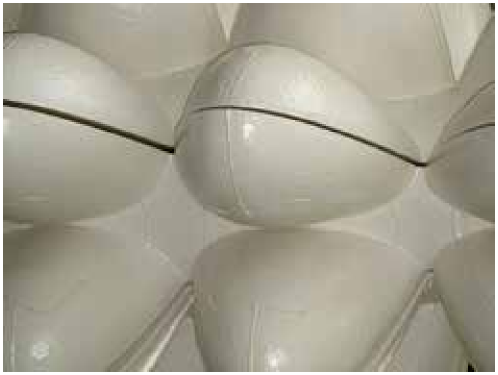

Figure 1
Multi Part Mold.

Figure 2
Sweaty Façade Components showing large surface area.

for shape optimization, prototype forms were then carved from polystyrene on a three-axis CNC router. Such complex objects present a distinct difficulty for traditional casting techniques. The more complex a desired form becomes, the more complex the formwork. Multi part formwork in ceramics is used traditionally to cast parts with large undercuts, or with surface area large enough to create impossible scenarios for demolding due to friction (Reijnders and EKWC, 2005).

The creation of these highly articulated façade prototype units was approached through a traditional mold making technique. A twelve part plaster mold was made by hand, including captured interior pieces held by ties piercing larger parts. The size of the pieces required a so-called "run-through mold" due to the sheer weight of the plaster. In order to empty the mold of liquid clay, a drain is placed at the bottom, which when opened allows remaining clay to drain from the form (Figure 1).

The resultant parts were deliberately designed to maintain the lines left behind by the seams of the mold in order to give clues to the making of the object (Figure 2). The large surface areas exhibited by these complex forms are impossible to accomplish using non-sculptorly techniques. Non-developable surfaces, in other words, must be carved or cast (Duarte, 2004).

A rendering of an architectural corner condition against the sky (Figure 3), shows a sensual façade based on repetitive ceramic elements. These elements are spaced to allow for air flow necessary for evaporative cooling between individual units, while the size and shape of the elements creates maximal surface area. The spacing and shape of the units is designed to minimize „slow" spots in the air flow, but also to provide for diffused daylight to pass through the screen to the building interior beyond.

Scaly Exteriors

The "bubble tile is envisioned as a ceramic heat exchange component which has a rough, darkly colored surface on one side, and a smooth reflective surface on the other side (Figure 4). Tiles can be used alone, or in conjunction with a liquid heat transfer system to move heat energy through an array of tiles. In an architectural building façade, heat exchange tiles can be placed in a mechanism which will allow the tiles to reverse front to back. This can allow infrared energy to be either reflected, absorbed, or diffused as necessary for environmental conditions in order to reduce heating and cooling loads on a building. By motorizing each tile, an array of heat exchange tiles can be used as a solar collector, heat exchanger, as a light shelf, or as signage. The technology takes advantage of the thermal properties of ceramics to modulate the heating and cooling loads on buildings in various climates. The function of the façade system is inspired by the Namaqua Chameleon (Benyus, 1997) which changes

Figure 3
Sweaty Façade Architectural Corner Condition. Rendering: Dan Greenberg.

color, depending on its needs, to either reflect or absorb the heat of the sun in the harsh and widely varied temperatures of the desert. Following this biomimetic strategy, the façade system will be programmable to alter its orientation to the sun based on material color, climate, and the needs of building occupants.

The creation of the positive forms for the bubble tiles relied on a simple parametric box-morph repetition of pyramidal forms over a simple shape using Rhino/ Grasshopper in order to achieve a device with maximal surface area on one side without creating micro shading conditions. The shape of the Bubble Tile poses an interesting problem for slip casting. The scale of the surface articulation is such that traditional mold making techniques become impractical; a multipart mold for this tile would contain many thousands of parts. The bumps on the surface are pyramidal in shape, so designed as to avoid micro shading of the component surface. In terms of the intricacies of mold making, this is the perfect shape for demolding, as it offers no undercuts to impede mold removal. Unfortunately, the bumps create such a massively increased surface area that the force of friction between the part and the mold makes removal of the part impossible. Additionally, large flat, hollow pieces such as this tend to collapse in the mold from the weight of unsupported wet clay. To solve these issues, an industrial slip casting technique was adopted.

Figure 4
Scaly Façade Component showing highly textured surface.

In the creation of the four part mold, a manifold of perforated air tubing was embedded in side of the mold corresponding to the highly textured surface of the part to aid in demolding (Figure 5). The mold is also pierced at the end by a plastic tube for pressurizing the interior of the part to stop it from collapsing.

The mold is filled with clay, and after sufficient thickness has developed in the interior of the mold, the remaining liquid clay is emptied. Immediately, the interior of the mold is pressurized through a short tube in the cap of the mold. Air pressure forces

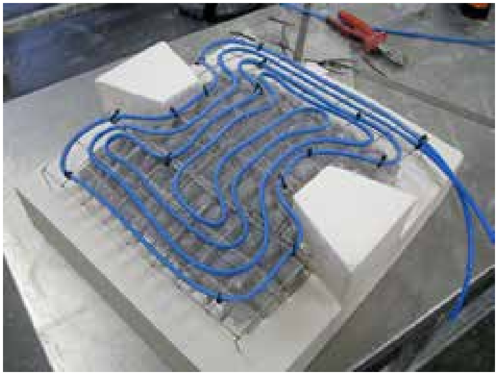

Figure 5
Perforated tubing laid prior to casting.

Figure 6
The highly textured mold interior.

the clay against the sides of the mold allowing the clay to harden without collapsing. As water is slowly absorbed from the clay into the plaster, the part becomes "leather hard" and is able to support itself. At this point, the interior pressure is released. In order to now demold the part, three bars of pressure is pumped into the perforated tube in the plaster. This air is forced through the pores in the plaster mold, causing water absorbed by the plaster to diffuse outward, ultimately creating a molecular mist of water at the exterior surfaces of the mold. This water, extruded at the interior surface of the mold (Figure 6), creates sufficient lubrication against the rough surface of the part to allow smooth part removal without breakage.

On a mockup of an architectural facade, (Figure 7), tiles are arranged horrizontally on the southern side of a building, and vertically on the east/west sides of the building. This redering places the concept in a generic glass box facade folly representative of a default retail or office condition suggestive of a energy sensible retrofit to an existing building. Tiles would be operable, allowing for maximization of absorbtion, reflection, or diffusion of heat energy, and to admit daylight and allow views as desired. The ceramic character of such a facade would allow for the creation of an architectural space reliant on rich materiality, while simultaneously providing a regionally adaptable high performance building.

CONCLUSION

The incredible complexities offered by the possibilities of advanced computation create opportunities for new advances in building performance. These complex forms, however, present unique challenges to traditional forms of manufacture for materials such as clay. A hybrid approach to the creation of complex ceramic parts leverages traditional and industrial techniques to produce manufacturing possibilities suitable for industry. This approach can allow designers to maximize material performance previously inaccessible in traditional materials, while simultaneously tapping into otherwise economically unfeasible material palette which, while firmly rooted in a progressive digital materiality, nevertheless recollects a hand-made past. Furthermore, progressive strategies for performance based design need no longer be the static fixed elements of our design past; instead, using biological models as a platform, architects have the opportunity to create buildings which sweat, change color, or otherwise adapt to their immediate environment with biological precision.

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Figure 7
"Scaly" Façade over a generic glass retail box. Rendering: Dan Greenberg.

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Generation, Exploration and Optimisation

Automated Simulation and Study of Spatial-Structural Design Processes

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Abstract. *A so-called "Design Process Investigation toolbox" (DPI toolbox), has been developed. It is a set of computational tools that simulate spatial-structural design processes. Its objectives are to study spatial-structural design processes and to support the involved actors. Two case-studies are presented which demonstrate how to: (1) study the influence of transformation methods on design instances and (2) study the influence of transformation methods on the behavior of other transformation methods. It was found that in design instances with the same type of structural elements the influence of a specifically varied transformation method is more explicit; while, when different types are present this influence is more undetermined. It was also found that the use of two specifically different structural modification methods have little influence on the sub-sequential spatial transformation method.*
Keywords. *Design process research; design process simulation; spatial design; structural design.*

INTRODUCTION

In the Architecture, Engineering and Construction (AEC) field, design processes are complex and multidisciplinary undertakings in which designers and engineers work together on the same problem to come up with feasible solutions. The final solution is usually the result of a cyclic process, in which the initial solution undergoes several changes and adaptations to meet pre-defined and arising requirements.

It is assumed that by improving the design process, the design outcomes will improve as well (Cross, 2008; Brooks, 2010; Kalay, 2004). Consequently, efforts have been carried out on the research of design processes, roughly subdivided in two categories: (1) the development and study of design models, which is the formulation of frameworks to organize the process of designing and (2) the generation of support methods or tools to aid in the design process. In the last category computational tools have been developed to increase productivity (Grobman et al., 2010), to ease the communication and the exchange of information between parties within the design process (Haymaker et al., 2004) and to take an active role on the design process and generate design solutions (Shea et al., 2005). However, little research has been carried out in which the computer is used to study the design process itself (Kalay, 2004; Coates, 2010).

The objective of the project presented in this paper is to increase the knowledge on spatial-structural design processes and consequently to support the involved actors. To that end a computational toolbox, a so-called “Design Process Investigation” (DPI toolbox) has been developed. More concretely, the DPI toolbox as presented in this paper, seeks to fulfill the following two aims: (1) to study the influence of a selected transformation method on design instance evolution; and (2) to study the influence of a selected transformation method on the behavior of the other transformation methods. The next section will briefly explain the DPI toolbox. Then a demonstration of the types of investigations which can be performed is shown, and lastly a short discussion and an outlook on further work are presented.

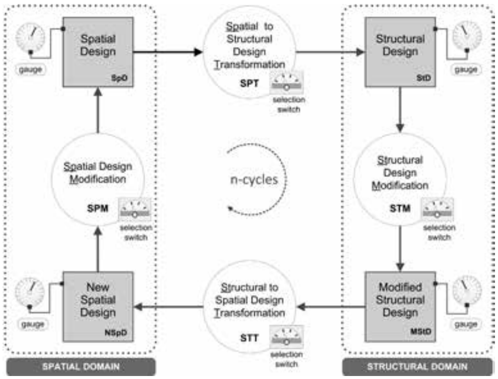


Figure 1
Design Process Investigation toolbox framework.

DESIGN PROCESS INVESTIGATION TOOLBOX

The DPI toolbox framework (Figure 1) prescribes specific and identifiable steps to reach a design solution. In that sense it could be categorized as a prescriptive design model (Cross, 2006). However, the objective of prescriptive design models is to ensure successful and consistent results; whereas the objective of the DPI toolbox is to simulate design processes so its outcomes and more importantly the process itself can be studied.

Design processes are cyclic and multidisciplinary tasks where both design solutions and design requirements undergo changes and adaptations before a definitive solution is achieved (Maher et al., 1996; Haymaker et al., 2004). Also, design requirements are usually “ill-defined” and the design process is often not recorded properly, so it is difficult to trace back or investigate the process later on. The DPI toolbox framework is developed to address those characteristics and problems of a design process.

The DPI toolbox framework defines the process to be followed. During this process a design instance is subject to four different transformation phases acting within or between the spatial and structural domains. It works as follows (Figure 1): First, a Spatial Design (SpD), in the spatial domain, is transformed into a Structural Design (StD) in the structural domain. Then, within the same domain, the StD is altered into a Modified Structural Design (MStD). After that, the MStD is transformed into a New Spatial Design (NSpD) that finally is altered into a Modified New Spatial Design (MNSpD), completing one full cycle. This cycle can be repeated causing the spatial and structural design instances to co-evolve. For co-evolutionary designs, no classical convergence criteria can be used to stop the process; but, if requirements (spatial design instances) and solutions (structural design instances) do not change anymore a (local) optimum is believed to be found (Maher et al., 1996).

Two other relevant characteristics of the DPI toolbox framework are: the “transformation and modification selection switches” and the “gauges” (Figure 1). These components have the objective of facilitating the study of the simulated design processes. The idea is to use the DPI toolbox to simulate different design processes, each with different transformation procedures, and to measure the resulting design instances, by the gauges, through the cycles for later comparison. In this way, it is possible to study the influence of transformation procedures on design instances and on sub-sequential transformation procedures.

Note that the DPI toolbox framework only prescribes the existence of a set of transformations, relations, and measurements (by the gauges) between two different domains within a cyclic design process; it does not define specific transformation or

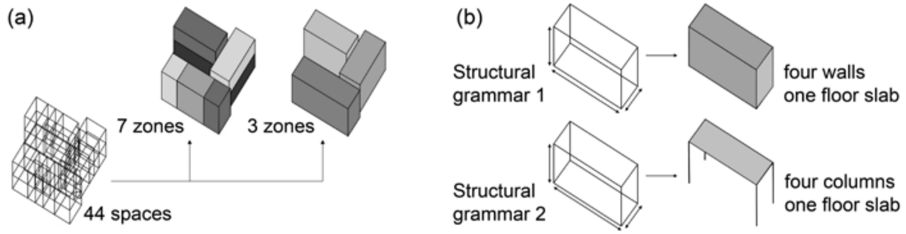


Figure 2
(a) Example of the zoning algorithm; (b) Two structural grammars used in the DPI toolbox.

measurement procedures. Thus, the selected transformation and measurement procedures used in the DPI toolbox are not unique in any way, and these used in this paper were chosen primarily for their availability. The procedures could be changed in the future to further study spatial-structural design processes.

As mentioned before, the DPI toolbox consists of four transformation phases and these phases will now be shown to consist of several stand-alone procedures, put together in a seamless process. Some of the used procedures have been widely studied and utilized in the AEC field, e.g. shape grammars, pattern recognition, and FEM simulations; others have been developed specifically for the DPI toolbox, e.g. geometrical redefinition and kinematic stabilization. Next, the four phases of the DPI toolbox, as implemented, will be briefly described.

Spatial to Structural Design Transformation (SPT)

The first phase generates a structural design instance and performs a FEM simulation with it, all based on the spatial design instance as used for input. The generated structural design only intends to formulate a starting point for the design cycles, and it does not intend to be an immediate optimal solution for the inputted spatial design. Likewise, the FEM simulation is not meant for stress engineering, but is merely used to give an indication of the structural behavior of the proposed structural design.

The Spatial Design consists of a set of volumes or "spaces". So far, the DPI toolbox is restricted to work with right cuboids, parallelepipeds bounded by six rectangular faces, so that each adjacent face meets at a right angle. Furthermore, the right cuboids or spaces should be aligned with the global coordinate system. The Spatial Design undergoes several transformations by procedures that are grouped in the following categories: (a) proposal of the structural design, (b) preprocessing, and (c) structural calculations.

The proposal of the structural design consists of two procedures: first structural zones are created and then, based on them, structural elements are generated. For the first procedure, the DPI toolbox uses an in-house developed automated 3D zoning algorithm (Hofmeyer and Bakker, 2008) (Figure 2a). It defines structural zones (elementary structural entities) based on sets of spaces. This procedure subdivides the Spatial Design into a number of zones, (grouped spaces) and these are used as a basis to generate structural elements. For the next procedure, structural grammars (Shea and Cagan, 1999) are used to generate structural elements. Structural grammars resemble shape grammars used in the AEC area (Stiny, 1980). They prescribe which structural elements can be used depending on the geometrical properties of the previously generated zones (Figure 2b).

Regarding (b) the preprocessing category, once a structural design has been generated, it has to undergo several procedures to be able to be simulated by a Finite Element Method (FEM). First, the geometry of the structure has to be redefined to ensure that all the finite element nodes will be coincident and to determine the wind loaded surfaces. Then the structure should be made kinematically determined, loads and constraints should be applied, and a meshing algorithm has to be performed.

Lastly, regarding (c) the structural calculations, the following procedures should be mentioned: A first-order linear elastic FEM simulation is carried out to predict nodal displacements in the structural design; then, the strain energy of each finite element is calculated. A clustering algorithm groups the finite elements into clusters based on their strain energy and a color-coded visualization is generated. The data obtained during this step will be the basis for the next phase's procedures, presented below. More information on this procedure can be found in (Hofmeyer and Davila Delgado, 2013).

Structural Design Modification (STM)

Having generated a Structural Design, the next step is to improve its structural behavior. Even though the procedures implemented in this phase follow closely those of traditional structural optimization, their objectives are slightly different. The objective of this phase of the DPI toolbox is not to obtain an optimal structural design per se, as in the traditional way, but to modify the structure only into the direction of an optimal design. Thus this phase is called Structural Design Modification rather than optimization.

This structural modification is based on minimizing strain energy. A structure that deforms under a given case of loads and constraints shows strains in its finite elements. The amount of strain energy in a finite element is a measure of its participation in bearing the applied loads. So, finite elements showing low strain energy can be regarded as being under-utilized and thus may be deleted. Two versions of existing structural optimization methods have been implemented in the DPI toolbox namely: Evolutionary Structural Optimization (ESO) and Topology Optimization (TO). A detailed explanation of this phase can be found in (Hofmeyer and Davila Delgado, 2013). Note that the version of ESO used has been modified so that only a single iteration is run in the optimization procedure (in this paper referred to as 1ESO). This is done because accurate enough results can be obtained and computation time is reduced.

Structural to Spatial Design Transformation (STT)

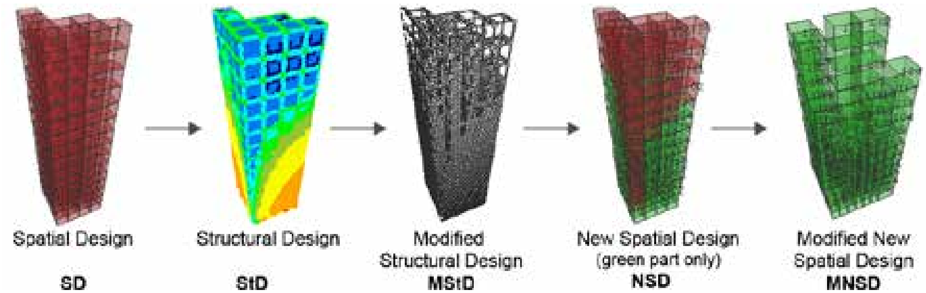
In this phase the MStD, an arrangement of structural elements, is transformed into the NSD, an arrangement of spaces. This is currently implemented as follows: First, it is indentified which finite elements have been deleted in the previous phase and to which space from the inputted Spatial Design they belong to (i.e. which deleted elements are contained within which space). Based on that information the spaces that contain many deleted (under-utilized) finite elements are removed. In other words, spaces that contain less elements contributing to withstand the applied loads, are in a structurally-seen less important zone, and are thus deleted (Hofmeyer and Davila Delgado, 2013).

For the current implementation, the first 30% of spaces with most deleted elements are removed, and then the remaining spaces are investigated. If spaces with the same number of deleted elements as the already removed spaces exist, they are removed as well. Note that in almost virtual case that all spaces have the same number of deleted elements, then only the first listed 30% of the spaces are deleted. This implementation is referred in this paper as "*Delete Spaces*".

Spatial Design Modification (SPM)

In this process, the NSpD will now be modified into a MNSpD that will serve as the input for a next cycle of the DPI toolbox. The main objective of this phase is to modify the NSpD for the next cycle such that at least some of the properties of the SpD, which may have disappeared during the transformations of the cycle, are restored. For example, in the end of the previous phase, spaces were deleted from the SpD and thus the NSpD has less volume and fewer spaces. Therefore, in this phase, the NSD could be scaled up to the same volume as the SpD and then some spaces within the NSD could be subdivided in order to restore the initial number of spaces. This phase is explained in more detail in (Davila Delgado and Hofmeyer, 2013) and it is referred to in this paper as "*Re-scale and Subdivide*".

Figure3
A typical DPI toolbox run.



DPI toolbox example run

Figure 3 shows a typical run of the DPI toolbox. Starting from left to right: the Initial Spatial Design; the Structural Design, here displaying its strain energy distribution; the Modified Structural Design where the under-utilized elements have been deleted; the New Spatial Design (green part only) where the spaces with more under-utilized elements (red) have been removed; and the Modified New Spatial Design, which has the same volume and number of spaces as the initial spatial design.

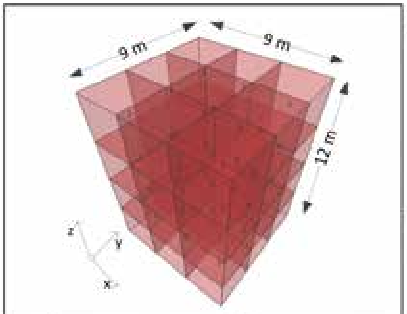
DEMONSTRATION

The main purpose of this section is to exemplify the types of investigations that can be performed with the DPI toolbox. Note that the cases presented here serve as a proof of concept and that in further stages of the research real-life and more complex case-studies will be performed.

Two case-studies are presented to demonstrate aims (1) and (2) as presented at the end of the Introduction section. In Case-study I, it is investigated how a change of the transformation method (a different structural grammar in this case) influences the evolution of the design instances (in this case structural designs) through the cycles. In Case-study II, it is investigated how a change of a transformation method (in this case 1ESO vs. TO for STM) influences the behavior of the sub-sequential transformation method (STT), again with respect to an observation through the cycles.

Figure 4 shows the initial Spatial Design used for both case-studies and the defined settings of the DPI toolbox respectively. For each case-study, two simulations (runs) have been performed, consisting of four cycles each.

Figure 4
Initial Spatial Design used for case-studies I and II; Tables list the respective DPI toolbox settings.



Spatial Design: 4 levels consisting of a 3x3 spaces as ground plan

*Number of clusters of finite elements to be deleted in STM.
**Divisions in which the structural elements will be subdivided.
***One zone is created for each space.

Case-study I	
I-A:	4 cycles
SPT:	
Zoning***	1space is 1zone
Grammars	**1roof-slab and 4 walls**
Loading	Gravity load
Divisions**	8
Deleted Clusters*	2
STM:	1ESO
STT:	Delete Spaces
SPM:	Re-scale and Subdivide
I-B:	4 cycles
SPT:	
Zoning***	1space is 1zone
Grammars	**1roof-slab and 4 columns**
Loading	Gravity load
Divisions**	8
Deleted Clusters*	2
STM:	1ESO
STT:	Delete Spaces
SPM:	Re-scale and Subdivide

Case-study II	
II-A:	4 cycles
SPT:	
Zoning***	1space is 1zone
Grammars	1roof-slab and 4 walls
Loading	Gravity load
Divisions**	8
Deleted Clusters*	2
STM:	**1ESO**
STT:	Delete Spaces
SPM:	Re-scale and Subdivide
II-B:	4 cycles
SPT:	
Zoning***	1space is 1zone
Grammars	1roof-slab and 4 walls
Loading	Gravity load
Divisions**	8
Deleted Clusters*	2
STM:	**TopOpt**
STT:	Delete Spaces
SPM:	Re-scale and Subdivide

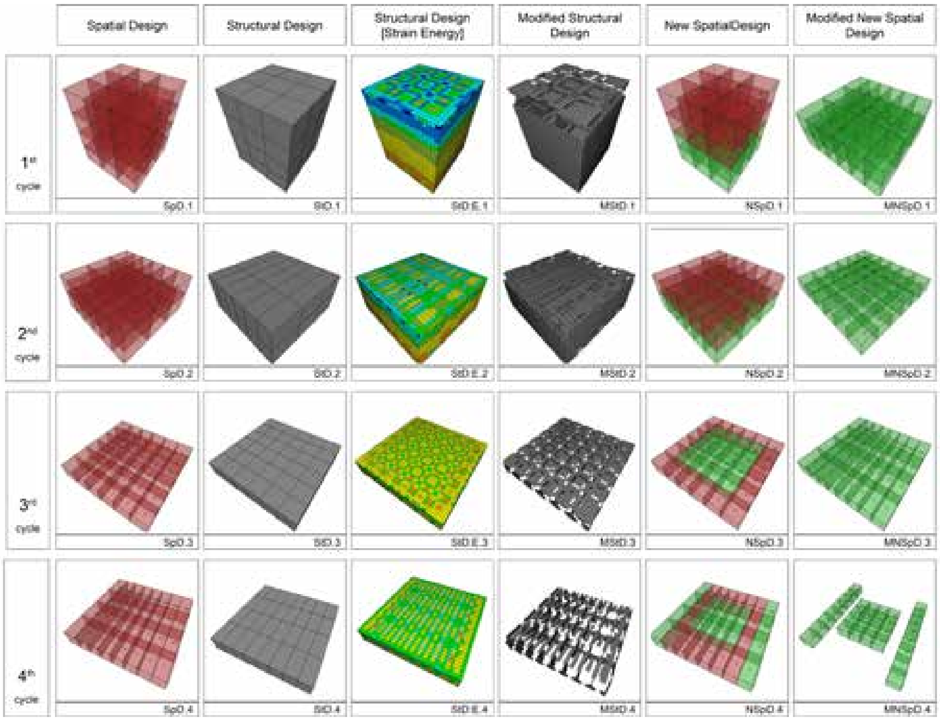


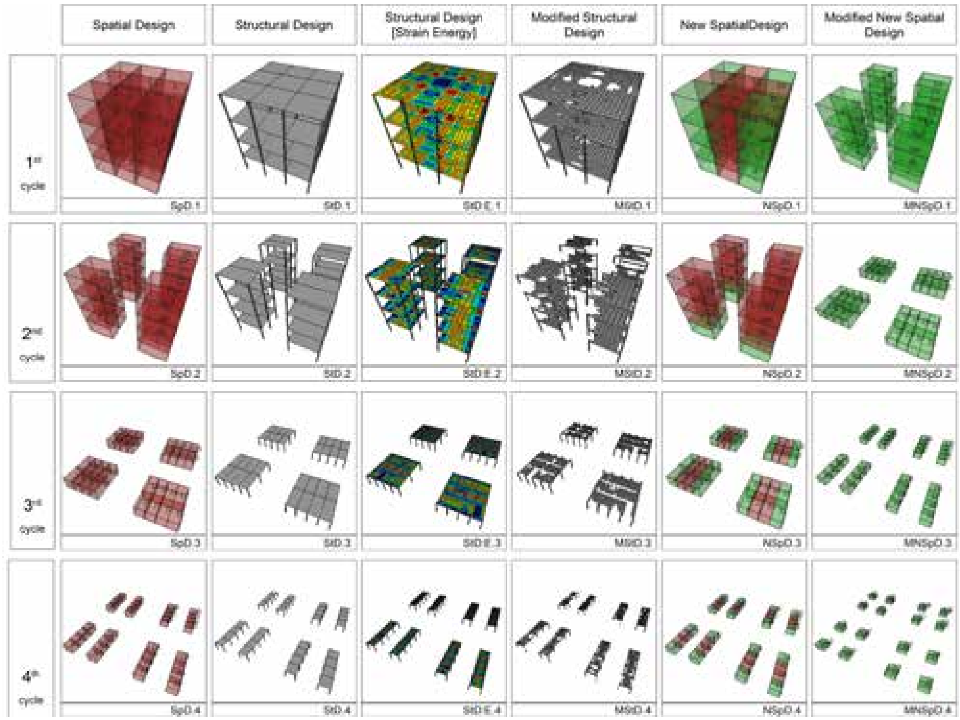
Figure 5
Resulting design instances for run I-A (which are the same as for II-A).

Case-study I

For Case-study I, two different runs have been performed: I-A and I-B, with structural grammars 1 and 2 (Figure 2b) respectively. All other settings were kept the same (Figure 4, table: Case-study I). Figure 5 and 6 show the resulting design instances of both runs (Note that the resulting design instances of case-study I-A are the same as those of II-A, so both are presented in Figure 5). In each figure, each row presents the results of one cycle, while the columns represent a phase within each particular cycle. Figure 7 presents the two measurements taken in each cycle for the design instance under investigation: the maximum nodal displacement (d_{max}) and the total strain energy (U_t). These measurements have been selected because they give an indication of the structural behavior of the resulting StD. A graph of each measurement through the four cycles is also presented in Figure 7.

For run I-A, it can be seen that d_{max} and U_t decrease at approximately the same rate at every cycle (Figure 7). This is probably due to the decrease of the number of building levels through the cycles. In Figure 7, on the top right corner of graph **b**, the decrease of levels through the complete run is plotted. That rate is similar to the rate of d_{max} and U_t. So it is not unlikely that there is a link between the number of levels in a StD and its d_{max} and U_t. Note that the spatial design instances in each cycle have approximately the same volume, number of spaces, and structural elements and that only dead load has been used as a load case. So, even though the structural mass of all the design instances is quite similar (Figure 7, table: Case-study I-A) -meaning that the total amount of load is quite similar as well- U_t is different. An explanation for the behavior above is that

Figure 6
Resulting design instances for run I-B.



in design instances with several levels the structural elements at the lower part of the structure have to withstand their own weight plus the weight of the structural elements on top of them and thus show higher strains.

In the last cycle the design instances have the same number of levels as in the previous cycle. Consequently U_t does not reduce significantly, but d_{max} does. This is because the horizontal structural plate elements that form StD.4 are rectangular, instead of square, and such elements tend to deform more.

For run I-B, using a different structural grammar, the evolutions of d_{max} and U_t follow the same pattern; but they do not correspond so clearly to the evolution of the number of levels, as in run I-A. In Figure 7 it can be seen that d_{max} and U_t increase seriously after the first cycle, even though the number of levels remains the same, and then decrease in each subsequent cycle. The initial increase can be explained by two reasons: (1) after the first cycle the design is divided into four fragments. In these fragments fewer columns have to support more roof-slab area and (2) the roof-slabs in StD.2 are rectangular, which deform more than square types. In both runs, I-A and I-B, d_{max} is always located at middle of the highest roof-slab so their dimensions (ratios) have a high influence on d_{max} and U_t. The second cycle's decrease could be explained due to the decrease in the number of levels, as observed in the previous run. Finally, the last decrease is due to the square shape of the resulting roof-slabs which deform less and thus yield less U_t.

In summary, during the evolution of run I-A a continuous decrease for d_{max} and (partly) for U_t can be observed. This decrease is directly linked to the number of levels of the design. Conversely, in the

Cycles		I-A: Flat-shells 1	I-A: Flat-shells 2	I-A: Flat-shells 3	I-A: Flat-shells 4	I-B: Columns 1	I-B: Columns 2	I-B: Columns 3	I-B: Columns 4
Maximum displacement	d_{max}	0.179604	0.0719628	0.0623938	0.0571595	0.348749	1.31948	0.732043	0.490521
Direction		uz	uz	uz	uz	uz	uz	uz	uz
Structural mass	m	178.2	169.4	162.8	142.7	65.8	74.5	64.8	70.15
Number of Levels	L	4	2	1	1	4	4	1	1
Total strain energy	U_t	244166	93140.5	41947.5	40565.6	80937.5	338001	203717	134220

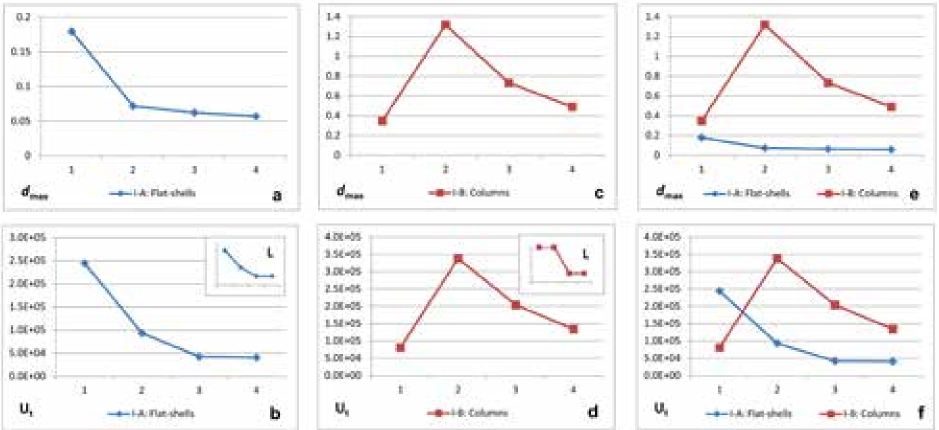


Figure 7
Result tables and graphs of runs I-A and I-B.

evolution of run I-B, no pattern can be recognized. This might be explained because in run I-A all the structural elements are the same; whereas for run I-B it is a mixture of flat-shells and columns.

Case-study II

Also for case-study II, two different runs have been performed: II-A and II-B, using 1ESO and TO for STM, respectively. All the other settings were kept the same (see also Figure 4, table: Case-study II). Figure 8 shows the resulting design instances of run II-B. Figure 5 presents the resulting design instances of run II-A, as they are the same as for run I-A. Figure 9 presents the two measurements taken in each cycle: the reduction of U_t and the difference between the number of spaces of the SpD and the NSpD. They were chosen because they are indicators of the performances of STM and STT respectively. Note that the TO procedure optimizes the structural design by decreasing the density of the less strained finite elements and increasing the density of the most strained ones. During this process, a "pseudo-U_t" is used (in fact a strain energy to the power of a certain penalty) which cannot be compared directly with the physically realistic U_t from 1ESO. For that reason the U_t values from run II-A were adjusted. This was done by (a) matching the density of the structural elements in the 1ESO calculations to the density of the first iteration of the TO procedure, and (b) by calculating the energy of the 1ESO calculations taking into account the power of the penalty. In this way, even though the U_t values are not "physically accurate" comparisons between the two procedures can be made.

The results tables of Figure 9 present the strain energy of the structural design before and after the STM procedure is performed, U_t and $U_{t\text{-final}}$ respectively.

Note that the U_t values of both runs are very similar. This is because they both have a similar StD (Figure 5 & 9) with the exception of the last cycle in which the StD -and thus the U_t- differs. Even though for both runs $U_{t\text{-final}}$ decreases at approximate the same rate, $U_{t\text{-final}}$ in run II-B is always lower. This is because TO minimizes U_t, while 1ESO minimizes structural mass, by deleting the structural elements

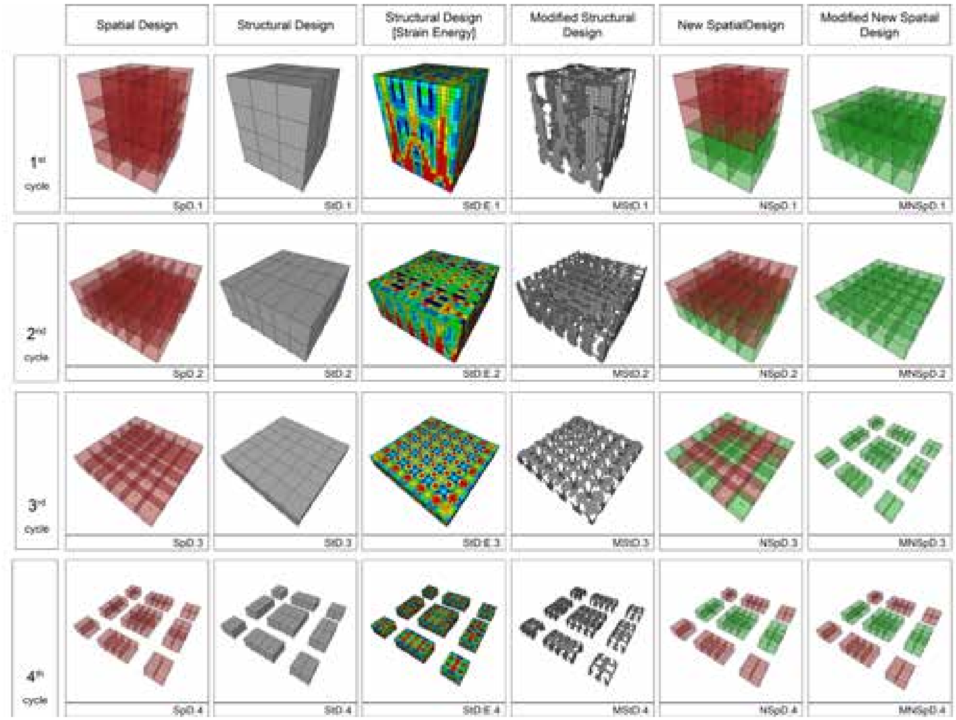


Figure 8
Resulting design instances from run II-b.

with less U_t. So in 1ESO, U_t is hardly reduced. It is also noticeable that the reduction of $U_{t\text{-final}}$ between two runs diminishes for every cycle. This is because in design instances with more levels *U* values among finite elements differ more, because due to gravity loads, finite elements at the bottom part of the structure yield more strain than the ones at the top part. So there is more opportunity for optimization in a structure with very dissimilar *U* values among its elements.

However, it can be seen as well that this difference in performance has little effect on the behavior of the subsequent transformation method (STT). For both runs, the specific spaces and the total number of spaces deleted by STT are the same during the first three cycles and it only slightly changes in the last cycle. Thus it can be said that within the current implementation, a different STM seems to have little influence on the behavior of STT.

DISCUSSION AND FURTHER WORK

The DPI toolbox framework and its current implementation were briefly presented. It simulates spatial-structural design processes to: (1) study the influence of a selected transformation method on design instance evolution; and (2) study the influence of a selected transformation method on the behavior of the other transformation methods. Two case-studies were presented, which illustrate the DPI toolbox's potential to aid in the study of design processes.

The first case-study investigated the influence of using a different structural grammar (a different transformation method) in the evolution of the structural design, via the maximum nodal displacement (d_{max}) and the total strain energy (U_t). It was

Cycles		II-A: 1ESO				II-B: TO			
		1	2	3	4	1	2	3	4
Initial strain energy	U_t	3,906,656	1,490,248	671,160	649,050	3,904,920	1,489,780	670,986	813,234
Final strain energy	$U_{t\,final}$	3,893,536	1,461,840	650,342	609,096	897,478	286,755	186,489	202,957
Number of spaces	S	36	36	36	28	36	36	36	32
Number of deleted spaces	S_{del}	18	18	20	14	18	18	20	16
% of deleted spaces	$\%S_{del}$	50%	50%	56%	50%	50%	50%	56%	50%

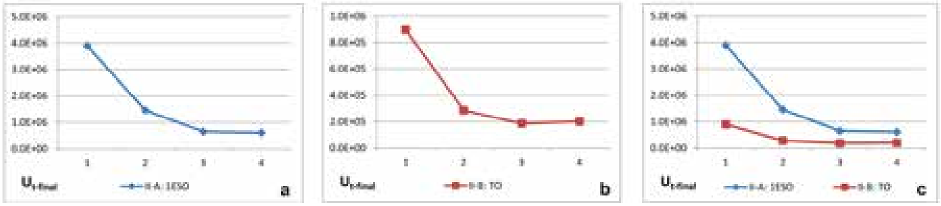


Figure 9
Result tables and graphs of runs II-A and II-B.

found that that in design instances with the same type of structural elements the influence of transformation methods is observed to be more explicit while, when different types are present, the influence is more undetermined.

The second case-study investigated the influence of using different Structural Modification Methods (i.e. 1ESO vs. TO) on the behavior of the subsequent Structural Transformation Method (STT). It was found that even though TO generates better structural designs than 1ESO, this has little effect on the behavior of the sub-sequential STT.

In the future, a further set of rigorous academic and real-life case-studies will be devised to benchmark the DPI toolbox. New transformation methods and amendments to the existing ones will also be implemented to further study the design processes.

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Generative Agent-Based Design Computation

Integrating material formation and construction constraints

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Abstract. *Agent-based systems have been widely investigated in simulation and modeling. In this paper, it is proposed that agent-based systems can also be developed as generative systems, in which different aspects of performative design can be defined as separate drivers in a proper computational framework. In this manner constrained generating procedures (CGP's) are studied to integrate the discrete design processes into one system. Subsequently, this generative agent-based design tool is accompanied with generating and constraining mechanism which are informed by material characteristics and fabrication constraints, bringing to the forefront emergent complexity.*
Keywords. *Computational design; agent-based system; robotic fabrication; constrained generating procedures (CGP's).*

INTRODUCTION

Performative design, as a design process, can be described along with several principles. Integrating such principles into a cumulative system is to involve different key aspects of performance in a process of formation. The integration process of these aspects requires designing a convenient generative system to explore performative approaches of form generation. In terms of computation, form can be defined as an interaction between internal components and external forces (Kwinter, 2008). Similar to natural morphogenesis, in computational design modeling the development of form can be informed by the process of materialization, production and construction (Menges, 2008). Each one of these internal components can be described as a separate driver, which in turn, can be synthesized into an integral computational design tool. These integrated drivers interact with each other within an environment, and exchange that ultimately increase the complexity of the system as a whole.

One procedural approach, is to organize such complexity through a computational framework that incorporates its own elements, rules and interactions (Holland, 2000). In some circumstances, this computational framework can exhibit emergent phenomena. In fact, the proper generative computational framework includes both mechanisms to generate possibilities and constraints to limit the range of possibilities (Holland, 2000). Moreover, this computational framework requires to be further specified during the problem solving design process; developing such computational framework involves three key aspects: *generation mechanisms, test mechanisms, and a control strategy* (Mitchell, 1990). Furthermore, based on constrained generating procedures (CGP's), the computational framework should have mechanisms to progressively adapt, or learn, as its components interact (Holland, 2006). A particularly promising method of modeling and simulating such complex adaptive systems (CAS) is agent-based system (Holland, 1995).

RESEARCH OBJECTIVES: GENERATIVE AGENT-BASED COMPUTATIONAL DESIGN

Recent advances in computational capacity open new perspectives into the implementation of agent-based systems as generative tools within computational design in architecture. The purpose of this paper is to investigate the possibility of integrating generative systems properties and constraint procedures into real-time computational form finding, which are coupled together to exhibit complex emergent behavior.

In this paper the development of this generative system is investigated through constraints generating procedures (CGP's). This approach gives the possibility to link simultaneously different mechanisms to generate and constraint possibilities, which allow for the exploration of emergent architectural solutions. These mechanisms contain discrete design elements and behaviors wherein bottom up methodology of behavior-based systems can be useful to organize emergent complexity. This integration is followed by a generative approach of material properties to explore performative formation in architectural practices, allowing form to emerge from the interaction between agent systems and their surrounding environment. In this investigation form generation is affected by different attributes, which are implemented inside the agents' data structure.

For this investigation, the agents' data structure is described by the specific geometrical behavior of bio-inspired plate structures based on the sea urchin. To achieve this, the agents are distributed on the topological space of UV map parameters; the relations between agent-agent and agent-environment are derived from this topological space e.g., it describes the conceptual neighborhoods along with its topological relations. In this context, the topological space is described by a surface with positive Gaussian curvature and by the fabrication tools, which consist of a KUKA KR 125/2 (6-Axis), and a KUKA KPF1-V500V1 turntable (1-axis). The fabrication configuration also includes a HSD ES 350 spindle unit as an effector.

GENERATIVE AGENT-BASED SYSTEM

Agent-based systems as a computational method, facilitates for researchers the study of various fields of science. An agent-based system consists of large number of agents that follows simple local rules and interacts within an environment (Gilbert, 2008). Agent-based modeling consists of defining both the agents and the relationships between them (Bonabeau, 2002); this can collectively exhibit a complex behavior pattern which leads to a global emergent behavior as a result. The individual autonomous agent, as a self-contained learning unit, perceives its environment and takes actions (Mellouli et al., 2004). Accordingly, the agent can learn from its surroundings by permanently repositioning itself within the overall agent-system and its environment - while adhering to a set of flexible behavioral rules. A system of agents thus has the ability to learn and adjust its behavior over time (Figure 1).

In social science, Gilbert (2008) illustrated that agent-based system can be classified into *urban models, opinion dynamics, consumer behavior, industrial networks, supply chain management, electricity markets, and participative and companion modeling* (Gilbert, 2008). On the other hand, Bonabeau (2002) categorized the agent-based system in a business context into *flows (evacuation, traffic), markets (stock market, shopbots and software agents), organizations (operational risk and organizational design), and diffusion (diffusion of innovation and adaptation dynamics)* (Bonabeau, 2002). These two classifications represent the application of agent-based system for simulation and modeling in any behavioral systems.

In the field of sociology, a generative agent-based approach has been regulated in two steps: Situating agents in a relevant spatial environment and after that utilizing agents' interaction based on

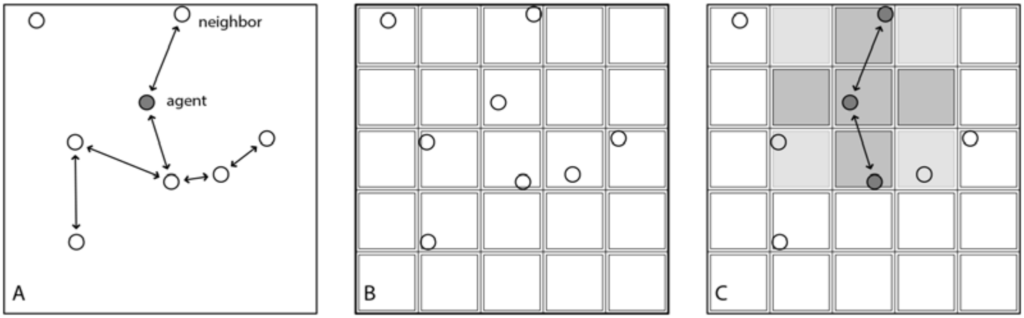


Figure 1
A: A Complex Adaptive System similar to that presented by Holland (1995); B: Agent distributions on the topological space; C: An Agent-Based System, topological interactions between agent-agent and agent-environment.

specific rules to generate another level of bottom-up organized regularities (Epstein, 2006). In this generative method, the systems' behavior cannot be deduced to behavior of their components, whereby it disregards some of the interactions between the elements (Squazzoni, 2012). Accordingly, the generative method in agent-based system is a bottom-up approach to take advantage of low-level features e.g., material properties, in a manner that enables emergent phenomena.

In relation to architectural design, developing such generative computational framework is easily associated to the different methods for establishing effective organized complexity. One of the features of such adaptation in complex system is emergent properties, which can be obtained through Constrained Generating Procedures (CGP's) (Holland, 2000). The advantage of CGP's in agent-based system provides the ability to define agents-based systems on mechanisms and constrains - in one specific system. This local generative system as a building block has been implemented in the computational framework as an overall generative system which can be identified as a system property. However, each one of these building blocks or agents has a data structure, in which the mechanisms and constraints have a great role to find an optimal solution.

Accordingly, the definition of mechanisms and constraints are critical in defining real time interactions within agent-based systems, whereby this definition must prepare the possibility for a system to become both generative and also have the capacity to exert the implemented constraints. This real-time interaction is relied on the agents' data structure; the agents perceive the environment as well the other agents, and based on their defined ontology compute the proper response to any stimuli (Pfeifer and Scheier, 2001). However, the ontology level also depends on the circumstances that will apply to the generative system. This knowledge distribution among agents could be specified locally in order to avoid unnecessary computation.

Consequently, the bottom-up knowledge distribution provides agent-based system with behavior-based computation rather than knowledge-based computation. In behavior-based computation, the topological space is explored with agents along with their specific behaviors to behave in this problem domain, rather than with a specific system that know about the problem domain (Maes, 1993). However based on emergence properties, this tool has difficulty approaching a precise behavior. Therefore, the underlying elements of this tool need enough flexibility to emerge an approximate behavior, as a cloud (Miller, 2007).

METHODOLOGY

Agent-Based system: Defining Mechanisms and procedures

In order to investigate a generative approach for an agent-based system, a CGP framework is developed with both generative mechanisms and constraints. This method maintains a generative computational framework to generate all the future possibilities, while maintaining specific constraints or limitations. The mechanisms of these generative agent-based systems are bound to material properties, fabrication and construction constraints.

Material properties in particular have the ability to characterize geometrical behavior mechanisms. In addition, motion behavior mechanisms have the ability to perform as a sensory motor for each one of these agents, where if the desired conditions are not being met, then the responsible mechanism will release an appropriate response to change the agents' behavior. This reaction can be differentiated by the agents' situation, which can be varied from splitting, eliminating, or re-orientation and relocation of the agents' situation. Predicting a proper mechanism for each situation or problem is not possible in a behavior-based bottom-up system, due to the low-level ontology that is used in it. For this purpose an agent-based system has to deal with only primitive ontology to solve the problems, wherein it has been situated. In the following sections some mechanisms related to this generative agent-based computational design tool will be investigated.

Motion Behavior Mechanisms: According to Reynolds (1999), the motion behavior mechanisms can be defined in three layers: *action selection, steering and locomotion* (Reynolds, 1999). These three behavior layers are applicable for a wide range of autonomous motion behaviors, however, it is necessary to mention here, that this behavioral hierarchy is not accessible to all range of autonomous agents e.g., it is not appropriate for *chatterbot* (Reynolds, 1999). In the other hand, the motion behavior mechanism is specialized in specific behaviors, which is imitated and modeled from certain behaviors of natural entities to relocate autonomous characters. Therefore, this mechanism is suitable only for changing the motion behavior of the system.

In *action selection*, agents observe the state of their environment and that of the other agents in order to perceive their changes. After this initial perception, agents set appropriate goals, which are proportion to the change of system state and synchronized to the agents' internal rules; in the *steering level*, the goal is decomposed into the sub goals that can be represented by the steering behaviors. This in turn can become steering signals, which are intelligible for the locomotion layer; in the *locomotion layer*, these signals will be converted into motion parameter of the agent's locomotion (Reynolds, 1999).

The agent-based system with Motion behavior mechanisms can be influenced by the other steering behaviors, at any moment; this is, to change the agent's location and orientation. The behaviors, which relate to the agent's motion, have to be translated to the steering behavior parameters. The steering behavior gives the possibility to accumulate different type of control behavior procedures and based on weight of parameters, they can change the agent's motion behaviors. Therefore, the locomotion mechanism must be completely independent from steering behaviors (Reynolds, 1999), in which the steering behaviors convert control signals into motion of agents (Figure 2).

Geometrical Behavior Mechanisms: Geometrical behaviors are directly affiliated to material properties which are used in the process of design, fabrication and construction. Therefore, the geometrical behavior mechanism is reflection of material properties. In fact, this mechanism defines interaction effects between geometrical characteristic of agents. Since, this investigation is about plate-like structures; therefore this mechanism is limited to the planes geometry. Hence, geometrical interactions between agents are related to geometrical planes intersection; wherein the intersection between a selected agents with surrounding agents, generates a cell with a polygonal structure. The distribution of agents on the topological surface, defines the final shape of agents' cell. The polygonal shape of this cell (e.g., convex or concave polygon) is closely related to the curvature of the surface (Troche, 2008), which the agents occupy tangentially. Due to the surface synclastic definition, the result will be a convex polygon.

The geometrical interaction between agents has been related to the tangent plane intersection. However the tangent plane intersection algorithm

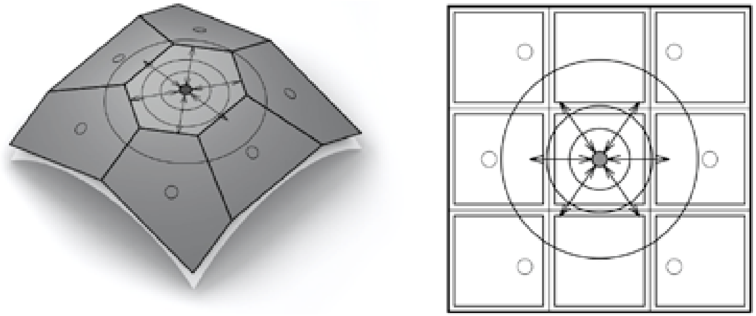


Figure 2
Motion Behavior mechanisms (the attraction and repulsion steering behaviors).

(TPI) (Troche, 2008) is not appropriate for defining geometrical behavior mechanisms, due to the knowledge-based structure which has been used inside the TPI algorithm. Instead of operating locally, the TPI algorithm works globally. Therefore an algorithm that is based on a bottom-up approach has been developed in order to calculate the real-time intersection between the plate-like structures of the agents' geometry.

Accordingly, the intersection mechanism has been developed to find the intersection vertices of a generating agent with other neighboring agents (Figure 3); these vertices lay on the tangent plane, which is approximately located on the surface. Furthermore, if the agent cell edges (with adjacent agents) are naked and not connected to them, then it indicates that the agent cell relations are interrupted with self-intersection or interpenetration of other agents. In that case, the generating agent need to send a steering signal to change its state in relation to the neighboring agents and environment.

Agent-Based system: Defining Constraints

As it is mentioned in CGP'S, the generative mechanism is coupled with constraints. In terms of architectural design, constraints can be associated with geometrical and fabrication requirements, which lead the generated outputs from interactions between mechanisms toward desired possibilities. It is critical to find a method to relate these interconnected design parameters as a part of the generative tool. In term of mathematical biology, the constraints can be described by morphological spaces, or morphospaces as mathematical spaces (Mitteroecker and Huttegger, 2009).

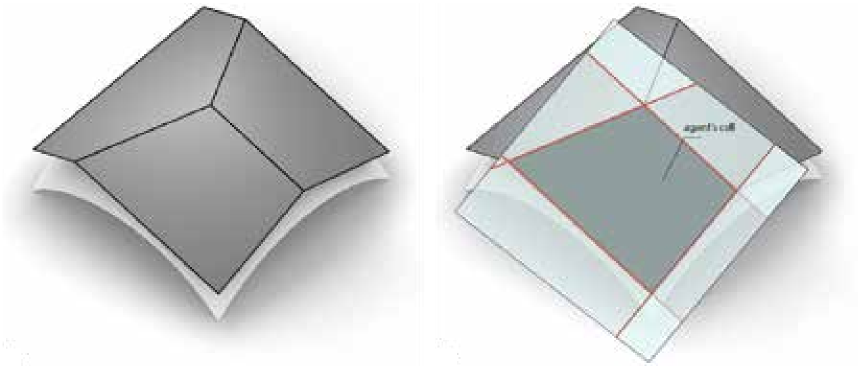


Figure 3
left: The generate agents' cell
right: The intersection mechanism by slicing algorithm.

The term morphospace, describes the morphological features of generative variations within *a solution space* or *landscape of possible outcomes* (Menges and Schwinn, 2012). In this generative tool, the constraints are considered from the geometric limitations and possibilities of the material characteristics. In the fabrication phase, these constraints can be described by the morphospace of the fabrication tool. In general, the agents' geometric attributes dictate the need for various procedures to utilize the generative interaction among the agents. However, the morphospace's definition overlaps with the differentiation between the geometrical possibilities and also being producible by the fabrication tool (Menges, 2013). Therefore, the constraints of this investigation are derived from the morphological space, which is categorized in geometrical, fabrication and construction constraints.

Geometrical Constraints: Since this generative tool is designed for plate-like structures, its geometrical parameters are applicable to the most probable range of plate structures. According to Menges (2013), the plate morphology is identified in three major features (Figure 4): 1) the *polygon radius,* which is defined as the area of the plate that is calculated based on the polygon vertices, and the perimeter circle which is bounding these vertices; 2) the *connection angle,* is defined as the angle between connected plates, which is calculated based on the angle between the normal of each connected plates; 3)the *polygon angle*, which is defined as the angle between the polygon edges and is related to the shape of the polygon (in the polygon convex segment(0° to 180°) and in the polygon concave segment(-180°,0°)) (Menges, 2013).

Fabrication and construction constraints: The morphospace of the fabrication tool, in relation to morphological geometry, represents the producible parameters of fabrication. As Menges (2013) mentioned, with the fabrication tools for this investigation, the morphospace region determines the producible of geometrical parameters: 1) the *polygon radius* depends on the distance between the robot and the turntable; 2) the *connection angle* is limited by the specification of the effector and the length of the tool; 3) the *polygon angle* is indirectly influenced by the fabrication tool, in which the constraints are related to the depth of joints who, in itself is determined by the connection angle (Menges, 2013).

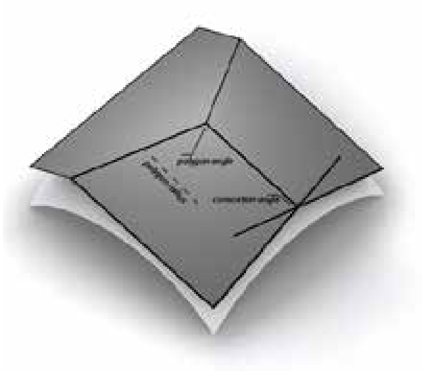


Figure 4
The geometrical and fabrication constraints: polygon radius, connection angle, and polygon angle; similar to that presented by Menges (2013).

RESULT: COMPUTATIONAL DESIGNING TOOL

Agent-Based system: Agent-based Programming

A generative agent-based computational framework is established by identifying the agent types along with their attributes (Macel and North, 2009). This identification will be followed by defining the boundaries within the surrounding environment that the agent will explore as a topological and morphological solution space. After the agents and environment are defined, this framework will simultaneously compute all parallel interactions between agent-agent and agent-environment. These parallel interactions will be associated by sending and receiving through a feedback loop (Holland, 2006). Accordingly, in the complex system behavior, convergence to the desired performance criteria is dependent on the positive and negative feedback loops.

This generative agent-based tool is initialized with agents (plate-like structures) and specific environment (synclastic surface). After initiation, the motion behavior mechanism is added to identify

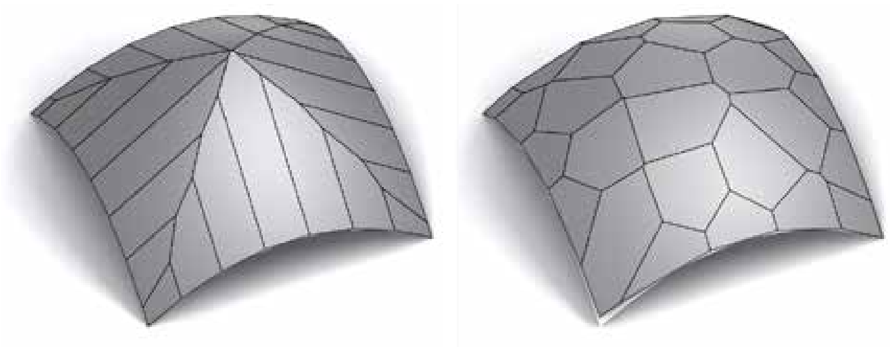


Figure 5
left: Edge adhesion (the attraction to the edges); right: Cell adhesion (the attraction and repulsion between agents).

the attraction and repulsion between agent-agent and agent-environment. Additionally, this mechanism is coupled to other control mechanisms for the rotation and repositioning of agents. However, after the agent distributions on the surface and the process of finding geometry interaction between agents takes place (generating cell for each one of agent), attraction and repulsion algorithms define coherency between the agents' cell and its environment. This coherency is defined by cell adhesion and surface edges adhesion. By increasing the value of the cell adhesion, agents begin to present flocking behavior and by decreasing it, agents start to avoid each other within the bounded surface. It should be noted that the agent-to-agent interaction is expressed between one agent and its closest neighbor or one agent and a range of its closest neighbors, in which each one of these can represent different behaviors. In the edge adhesion, by increasing the adhesion value, agents will be attracted to the edges and by decreasing it they will gather in a central position - away from all edges (Figure 5).

Consequently, in geometrical behavior mechanism, it would be necessary to avoid inappropriate intersections between connected cells. This problem occurs when the edge intersection lies outside the overlapping boundary area between the two cells. In this case, an algorithm controls that the right intersection between cells exists, it does this by rotating the cell or by relocating it on parallel to its normal (Zimmer et al., 2013); through this process the intersection point will gradually change its location until it fits inside the defined area (Figure 6).

The main functional component of any generative system is it capacity to constrain the possibilities, which are emerged from the generation mechanism. According to the defined constraints for this investigation, the generated cells need to be limited by two aspects: size of the agent's cell or polygon radius, and the angle between agents' cell or connection angle. The cell size can be deduced by a regular polygon area formula for convex polygons, after which the radius polygon can be obtained; this radius will be stored in the agents' data structure to be accessible by the agents during the computation. However, the polygon radius must be in the specific range imposed by the fabrication constraints, in order to change the size of the cells, cell division and

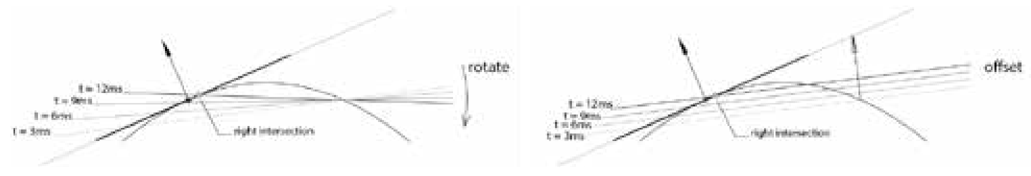


Figure 6
left: Rotating the cell to find the right intersection; right: Relocating the cell on parallel to its normal.

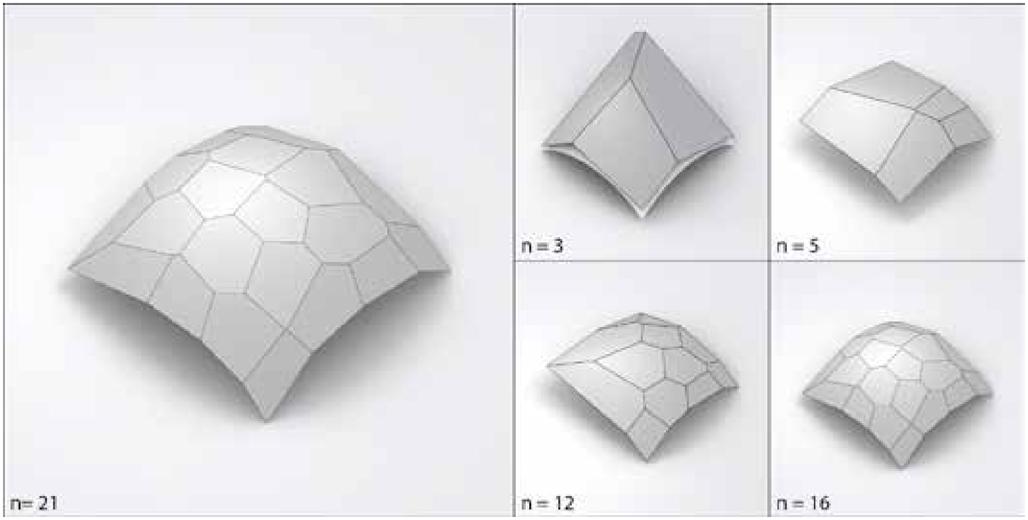


Figure 7
Finding the right polygon radius through the cell division and cell growth mechanism.

cell growth mechanisms are developed to maintain this size. Additionally, if the polygon radius becomes lower than a predefined size due to the fabrication constraints (as a result of the robotic morphospace) an elimination mechanism will remove the cell from the investigation (Figure 7).

The connection angle is obtained through the normal of the connected cells. Through this arrangement, the angle controller mechanism finds the angle and checks it for conformance. If it is necessary, the controller generates a steering signal to rotate the cells- this is executed recursively until it reaches the range required for connection angle. This mechanism is developed to calculate the steering signal for a generating cell and all its adjacent cells (Figure 8).

DISCUSSION AND CONCLUSION

Current research has proven effective in implementing such workflow in the presented case, where robotic fabrication principles of the plate structure morphology have been transferred into the agent's attributes. For this transfer to be effective, it is necessary to precisely investigate and analyze the biological plate structure. Although in modeling of the complex system it is not possible to reach a perfect abstraction; it is possible to find the general behavior of the plate structure. This behavior will form the basis of the bottom-up mechanism. This bottom up approach, provides the generative system with the possibility to exhibit emergent plate-like structure arrangements and patterns. For example, a prelimi-

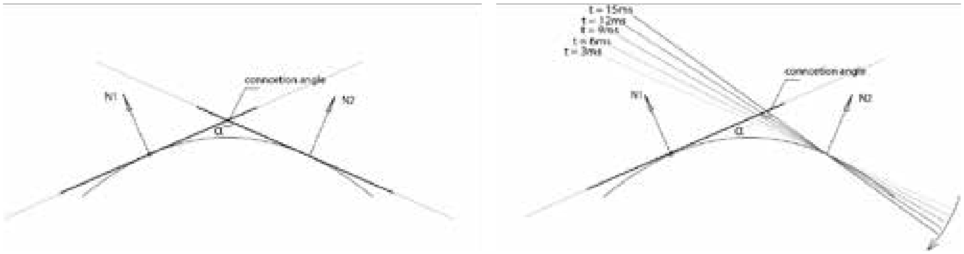
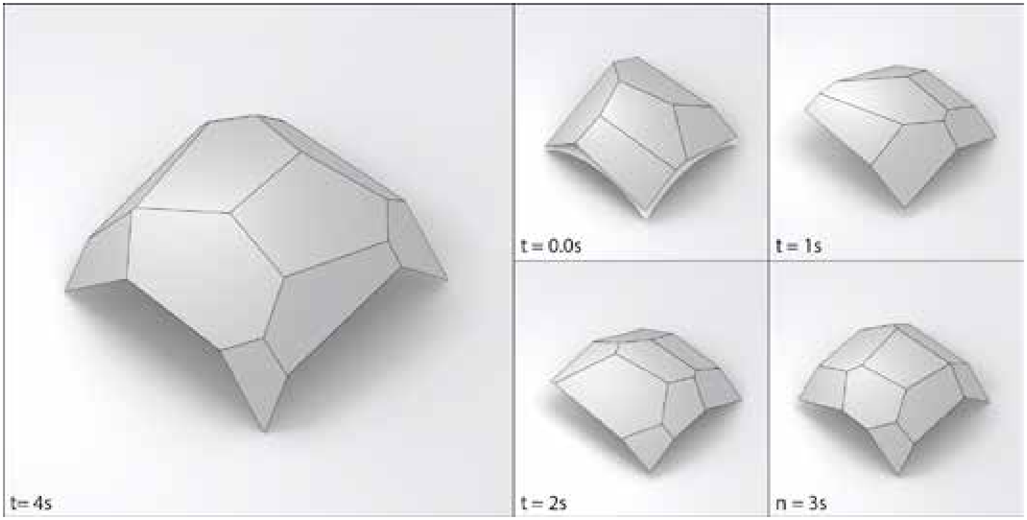


Figure 8
controlling the connection angle by generating a steering signal to rotate the cell.

Figure 9
the final result of the generative agent-based computation tool.



narily result of such generative system presented joint conditions that were similar to the Sea urchin, where three plates meet each other at one corner point – rather than four. However, although this behavior was anticipated, it is also discernible that the lack of construction mechanisms (which naturally has been used in the plate structure), along with insufficient construction constraints caused the initial result to be far from what was expected. The initial results might be enhanced by further analysis of biologic model, the fabrication space and the agents emergent behavior so that additional mechanisms and constraints can be subsequently implemented into the tool.

It is also possible to speculate that the results are indicative of the specific means in which agent based tools process the input data. Unlike "Motion behavior" (Reynolds, 1999), the generative agent-based deals with the implementation of material characteristics, geometrical behavior and construction constraints; this implementation affects agents' behavior locally and globally. In this manner, agents become a complex adaptive system of systems. It is speculated in this paper that although the presented case studies in the generative agent-based tool can be accommodated within computational design-, it is imperative to differentiate the aspect of the generative agent-based computation that contribute to integrate material system as mechanisms with robotic fabrication constraints (Figure 9).

Some of the consequences of this implementation might steer in a different direction expanding further our understanding into the Morphospace of robotic fabrication (Menges, 2013). For example, angle and plate control mechanisms empower the design construct in a way that facilitates access for the designer to methodologies that allow him to achieve an optimized plate formation; they also reduce the need to recourse to design process during construction phase.

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Evolutionary Energy Performance Feedback for Design (EEPFD)

Interaction and automation for a design exploration process framework

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Abstract. *In order to understand the applicability of multidisciplinary design optimization (MDO) to the building design process, a MDO framework, titled Evolutionary Energy Performance Feedback for Design (EEPFD), along with the prototype tool, H.D.S. Beagle, were developed to support designers with the incorporation of partially automated performance feedback during the early stages of design. This paper presents 2 experimental case studies, one from the design profession and the other from a design studio, that evaluate the applicability and impact of EEPFD on the early stage design process. Through these two case studies two different interaction and automation approaches for applying EEPFD are explored as part of the framework validation. Observed benefits, challenges and suggestions of EEPFD's implementation are then presented and discussed.*
Keywords. *Conceptual energy performance feedback; design decision support; performance-based design; multidisciplinary design optimization; genetic algorithm.*

INTRODUCTION AND MOTIVATIONS

In the interest of promoting sustainable design, energy consumption has become increasingly significant to the overall design process for architecture and building engineering. However, there is currently little direct or validated feedback between the domains of energy simulation and the early stages of the design process where such decision making has the greatest impact on the overall design's performance and lifecycle. Acknowledged obstacles include: disconnection between and the lacking of domain knowledge, tool interoperability, intensive analysis time requirements, design cycle latency amongst a diverse set of design expertise, and limitations of design cognition and complexity as previously researched in numerous precedents (Augenbroe, 2002; Oxman, 2008; Attia et al., 2012). Consequently, performance assessments are typically made after the initial design has been finalized with a limited set of explored design alternatives, as opposed to earlier design stages where a broader range of potentially more optimal solutions may exist (Radford and Gero, 1980). In addition, designers must balance the needs of multiple competing objectives, often through inefficient and imprecise means, to identify the best fit design through an understanding of trade-offs between energy performance and other design objectives.

The motivation of this research stems from the potential of multidisciplinary design optimization (MDO) methods to alleviate issues between the design and energy simulation domains. MDO is a general term used in reference to the method of coupling parametric design and optimization algorithms in an automated or semi-automated design process framework or workflow with the intent of identifying "best fit" solutions to complex problems with competing criteria. MDO methodologies have been successfully adopted in the aerospace industry and other engineering fields and have been gradually explored in the building industry as a means of potentially mitigating existing issues between building design and other performance analysis domains. Current research into applied MDO has initially demonstrated a capability to overcome interoperability issues between domain specific platforms. Optimization algorithms automated by MDO have also been identified as being capable of increasing feedback results and designer interaction. By virtue of the automation and optimization more efficient access to performance evaluations of design alternatives inclusive of trade-off studies between competing design criteria in support of design decision-making is also indentified (Flager et al., 2009; Yang and Bouchlaghem, 2010). Given the trend of computing availability, e.g. cloud computing our research into MDO is becoming more obviously suitable to the particularities of the architectural practice. We hypothesize this computing trend results in an exponentially expanding potential of MDO applicability. When observed in the context of this expanded computing capability, the plausible bridging of the observed gap between energy performance and design through MDO serves as another driving force behind this research. MDO is therefore understood as a key component to achieving the research motivation of "designing-in performance" which is defined in this research as the idea of utilizing performance feedback to influence design exploration and subsequent decision making under the assumption of pursuing higher performing designs much earlier in the design process and arguably intrinsically coupled, not the norm in contemporary practice.

PROBLEM STATEMENT AND RESEARCH OBJECTIVE

While current precedents in the building design industry demonstrate the potential of MDO as a means of solving performance feedback issues, there are several inherent and unique challenges for MDO to be more robustly and pervasively applied in architectural practice. For example, when MDO is applied to the aerospace industry an identified "best fit" solution can be mass-produced once it has been fully optimized. In comparison, to apply MDO to find a best fit for building design problem always with a unique set of requirements, circumstances, and preferences appears less cost effective by nature. In addition, the objective nature of evaluating design in other engineering industries provides more suitability towards MDO application than the more subjective nature of building design, where architecture is inclusive of aesthetic motivations as well. Furthermore, a deep rooted disconnection between design and energy simulation domains, enumerated previously adds to the factors impeding the application of MDO to be fully explored and implemented within the design and energy simulation domains. Another of our research observations is that the majority of the MDO applications in architecture related to building energy performance are conducted by researchers predominantly engineering based with a focus on optimizing mechanical systems or façade configurations, typically much later in the design process after the building envelope has been finalized (Wright et al., 2002; Adamski, 2007). The importance of form exploration during the early stages of the design process is to date seldom addressed and typically through overly simplified geometry for proof of concepts observed to be due to the limited flexibility of existing frameworks (Tuhus-Dubrow and Krarti, 2010; Janssen et al., 2011). Furthermore, there is only a limited number of published MDO frameworks for building energy performance that have been fashioned and explored through a designer's perspective (Caldas, 2008; Yi and Malkawi, 2009; Janssen et al., 2011). Yet, within these applications, emphasis on the applicability and designer interaction of MDO frameworks for the early stage design process have not been adequately researched.

In response to this existing gap –emphasizing the early stage of design and design exploration stages- and the potential of technological affordances and trends, a design centric MDO framework, titled Evolutionary Energy Performance Feedback for Design (EEPFD) was developed and has been initially tested and benchmarked against conventional design processes to understand applicability to the early stage of design (Gerber et al., 2012). The objective of this research step presents a focus on the issue of designer interaction within EEPFD through observation of two case studies: 1) a practice based case study involving a K-12 facility; and 2) a design studio based case study involving a single family residence. To provide a consistent point of comparison a series of measurements regarding design alternative performance, process efficiency, as well as designers' interaction and communication with EEPFD are established, collected, then discussed. Through a comparative study of these two processes adopted by these designers, the applicability and impact of EEPFD during the early stage of the design process is then presented.

THE FRAMEWORK: EVOLUTIONARY ENERGY PERFORMANCE FEEDBACK FOR DESIGN

Evolutionary Energy Performance Feedback for Design (EEPFD), a design centric MDO framework, is developed to incorporate conceptual energy analysis and design exploration of simple to complex geometry for the purpose of providing early stage design performance feedback (Gerber et al., 2012). It is intended to be used by designers during the conceptual design stage where overall building form has not been finalized. EEPFD utilizes an automated evolutionary searching method and a custom genetic algorithm (GA) based multi-objective optimization (MOO) algorithms, to provide energy performance feedback (i.e. energy use intensity (EUI)) to assist in design decision making. Also included are spatial programming compliance (SPC) and a schematic net present value (NPV) calculations for consideration in performance trade-off studies. The automation engine of EEPFD was developed as a prototype plug-in for Autodesk® Revit® (Revit), titled H.D.S. Beagle, to integrate design, energy, and financial domains. The integrated platforms are Revit, Autodesk® Green Building Studio® (GBS) and Microsoft® Excel® (Excel) respectively. The three competing objectives in the algorithm are to maximize spatial programming compliance (SPC), minimize energy use intensity (EUI), and maximize net present value (NPV). The detailed functionality of each platform, objective functions, and GA-encoding method can be found in previously published work (Gerber et al., 2012).

The process of applying EEPFD to obtain performance feedback for design decisions is illustrated in Figure 1. The first step has two subcategories: the generation of the initial design and the generation of design alternatives. In EEPFD, the initial design is generated by the user through a parametric model in Revit and a constraints and parameter range file in Excel. At this point the initial geometry, parameters and ranges, site information, program requirements, and available financial information are provided manually by the user. As a result, in order for designers to use EEPFD, it is essential for them to have the ability to formulate their design problems in the form of a parametric model in Revit with their exploration interests translated into a series of parameters and ranges. An understanding of and capability with parametric practices, solution space thinking, and design exploration is an essential prerequisite in the implementation of EEPFD (Gerber, 2007). The generation of design alternatives is part of the automated process driven by the customized

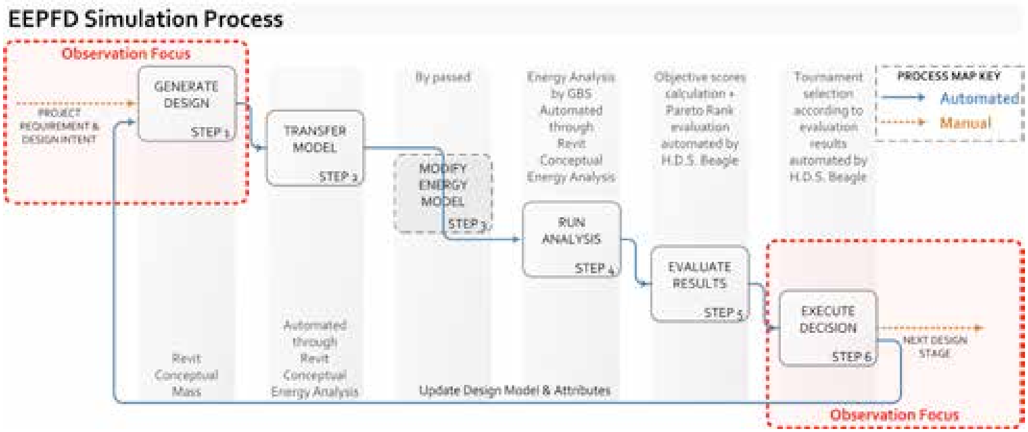


Figure 1
EEPFD's illustrated simulation process in accordance to the identified six step conventional energy simulation process. Highlights are the observation foci of this paper, emphasizing the interfaces inclusive of the interaction between designers and EEPFD.

GA-based MOO in EEPFD. Once the initial design is modeled and entered into the automated system, the following steps are then cycled through until the automation loop is terminated either by the user or by the meeting of the system's termination criteria. Once the automation loop is terminated, there are two ways of proceeding: 1) a design alternative is selected based on the multi-objective trade off analysis provided by EEPFD and the design proceeds to the next stage of development or; 2) the user manually implements changes in the initial design or constraints file based on the provided feedback before reengaging the automation loop. A detailed description of each step and the process of applying EEPFD implemented by users can be found in previously published work (Gerber and Lin, 2013). Currently, EEPFD has demonstrated the ability to automatically breed, select, evaluate and identify better fit design alternatives for varying degrees of building typologies and geometric complexity. EEPFD has also been validated against the human decision making process and is able to provide a solution space with an improved performance over a manual exploration process (Gerber and Lin, 2013). This paper further validates EEPFD with a focus on understanding the usability of the framework by designers, which is described and measured through their interaction with EEPFD prior to and after the automation system has been engaged, as highlighted in Figure 1.

RESEARCH METHODS AND EXPERIMENT DESCRIPTIONS

To explore the applicability of EEPFD to the design process this research provides an environment in which the interaction between designers and EEPFD during the early stages of design is observed. This research presents two case studies observed in this manner; Case Study I as a practiced based study involving a K-12 school design, Case Study II as a design studio based study involving a single-family residential design. In both cases the general program layout and overall building envelope design concept has be decided upon, as illustrated in Figure 2.

Through these case studies, two methods of implementing EEPFD were explored with a divergence occurring during the two steps of EEPFD that require human interaction. While both case studies followed the previously described six step process, Case Study I requires a consultant to provide technical expertise while Case Study II requires only minor technical support. In both cases the authors served as the technical process experts, thereby bypassing any technical complications encountered through the prototype's use, and were available throughout the process to provide necessary technical support

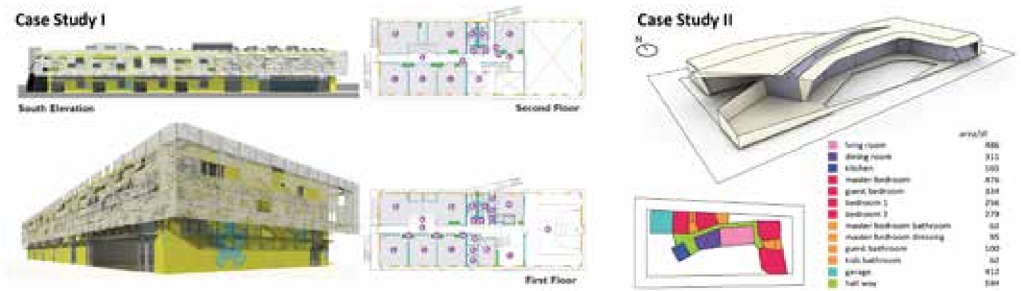


Figure 2
Case Study I and Case Study II conceptual design development before initial engagement of EEPFD. Image courtesy of Xinyue Ma (Case II) and Swift Lee Office (Case I).

and to enable direct observation of EEPFD on the early stages of this design process and design team.

The specific focus of our research observation is the interaction between the designer and EEPFD in the initial problem formulation and utilization of generated data, steps 1 and 6 as shown in Figure 1. During this study three aspects of performance are considered and discussed. The first performance definition is that of the generated design alternatives as measured through the set of three objective functions when compared with the initial design. This represents the affordance of the current technology and the built in evolutionary search method of EEPFD. The second performance definition is overall quantity and quality of feedback generated through EEPFD. In this research the qualitative and quantitative analysis data regarding the design problem, process, and product was collected and compiled into the metrics defined in Table 1, which summarizes the recorded data during the explora-

Table 1
Utilized evaluation metrics, categories, recorded data and units of measure in this research step.

	Recorded Data	Data Type
Design Problem Measurement		
Project Complexity	1. Project type	descriptive
	2. Project size	sqft
	3. Space type number	number
Design Complexity	1. Energy model surface count	number
	2. Explored parameter numbers	number/ descriptive
Design Process Measurement		
Speed	1. Time spent to create design geometry	minutes
	2. Performance feedback time per result	minutes
	3. GA settings	
Design Product Measurement		
Feedback method	1. Feedback number per 8 hours	numbers
	2. Solution space quantity - feedback design alternative number	descriptive
	3. Solution space quality - solution space range in NPV, EUI and SPC. Pareto solution number	
Actor		
Actor	1. Main actors role	descriptive
Experience	1. Parametric model experience	descriptive
	2. Energy simulation domain experience	descriptive

tion processes. Overall, quantity is defined as the number of design alternatives analyzed and time required for each analysis, while overall quality is defined by the number of Pareto solutions generated by EEPFD. The final performance metric is that of the observed design process itself when compared and contrasted with the six step simulation format of the experimental design scenarios. Particular emphasis is placed on the observed interaction between the designers and EEPFD and their ability to 1) identify and translate their design objectives and intentions into a functional parametric model for the system, and 2) the perceived relevance of the overall results by the designers to assist in their early stage decision-making.

DESIGN PROCESSES AND RESULTS

Case Study I: Practice Based Project

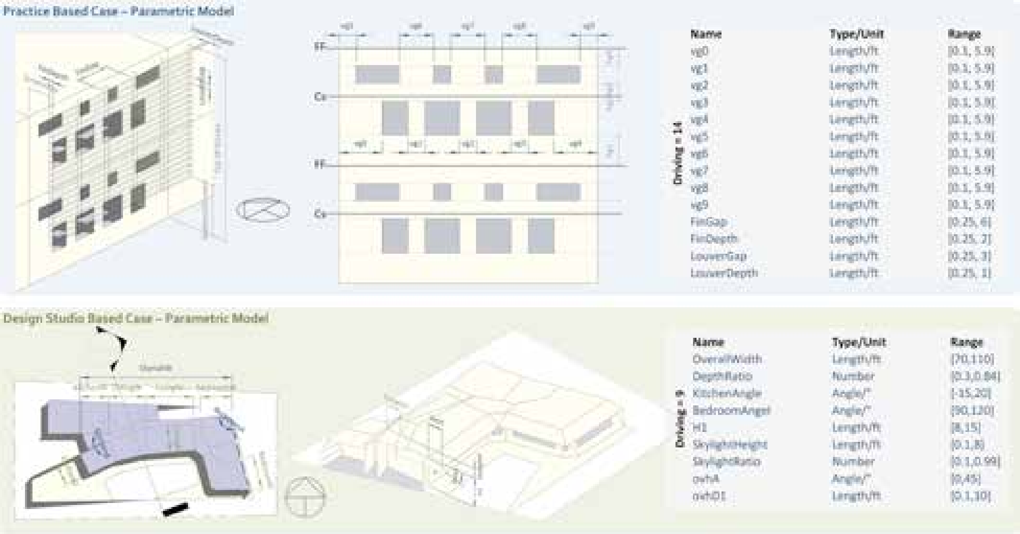
Case Study I focuses on a K-12 school design with approximately 30,000 square feet of usable program space using a method allowing for easy adaptability to multiple sites throughout the greater Los Angeles area. Due to flexibility requirements by the client, a kit-of-parts design concept was developed to allow for multiple site adaptability and to allow for future reconfiguration for various educational uses. In addition the pursuit of a net Zero Energy Building configuration for each site was added to the design goals by the designers.

For Case Study I, the designer role was filled by the two principal architects whose design philosophy of doing "the most with the least" focuses on economical and sustainable qualities as prerequisites to design. While the designers for Case Study I demonstrated an interest in utilizing innovative technology and methods, neither designer had any experience with parametric modeling or the Revit platform prior to this case study. Prior to this case study, however, the designers did have experience with attempts to integrating performance feedback as part of the design process with both in-house performance analysis and collaboration with an outside MEP consultant. While energy performance feedback was made available through the prior two approaches, the ability of these approaches to provide relevant information at the speed necessary for supporting the designers' rapid determination of optimal configurations for different site conditions was still in question. As a result, the implementation of EEPFD was explored and researched by the designers and research team to understand whether EEPFD could provide a suitable alternative approach.

In Case Study I the design problem itself was limited to optimizing one standard classroom unit using the defined kit-of-parts through manipulation of varying façade elements. As parametric design had not been a part of the designers' practice prior to this experiment, the authors served as consultants to assist in the translation of the design into a parametric model. Due to unfamiliarity with parametric modeling, the Revit design platform, and the inherent limitations of both, a week and four iterations were needed before the parametric model could be finalized. The parameters explored for façade configurations included customized opening sizes, solar screen depth, density, and mounting distance from the building, as illustrated in Figure 3. Following the completion of the parametric model, necessary supplemental information regarding financial estimates, material properties, etc. was compiled by the authors. In order to closely emulate the future implementation process, the financial model of this experiment was calibrated according to the cost estimation of the project. Also the material assignment and HVAC assignment were based on prior guidelines provided by the MEP consultant.

Figure 3 illustrates the collected data and resultant solution space in a quantified format. Through the GA run by EEPFD a total of 384 design alternatives were generated over a period of 4 hours with an average speed of less than a minute per result. The solution space improved from the initial EUI = 70.08 to 69.30 kBtu/sqft/yr and NPV from -0.51 to -0.48 million dollars. Since the program explored was fixed in value, the SPC score remained consistent throughout the generated solution pool. After

Figure 3
(Top Left) parametric model of Case Study I. (Top Right) parametric model of Case Study II. (Bottom) the collected quantitative measurements of Case Studies I + II according to the established metric.



	Design Problem Measures					Design Process Measures			Design Product Measures		
	Main Actors	Project type & size	Initial energy model surface no.	Space type no.	Explore parameter no. (design/energy)	Time to formulate design	Feedback time per result	GA settings	Feedback no. per 8 hours	Total solution space quantity	Solution space quality
Practice Based Case Study	Designer Design intent + Consultant Parametric modeling + Run H.D.S. Beagle	one classroom of a K-12 School 1,885 sqft	156	1	14 / 0	Approx. 2 week	0.63 min.	Initial population no. = 24 Population no. = 24 Selection size = 12 Max. gen. no. = 16 Crossover ratio = 0.7 Mutation ratio = 0.01	762	384 Approx. 4 hrs.	Initial NPV = -0.32 million $ Initial EUI = 70 kBtu/sqft/yer Initial SPC = 100 NPV = -0.56~-0.24 million $ EUI = 69~72 kBtu/sqft/yer SPC = 100 Pareto solution no. = 46
Design Studio Based Study	Designer Design intent + Parametric modeling + Run H.D.S. Beagle	Single Family 3,000 sqft	197	7	9 / 1	Approx. 2.5 months	0.91 min.	Initial population no. = 20 Population no. = 20 Selection size = 20 Max. gen. no. = 50 Crossover ratio = 0.6 Mutation ratio = 0	597	1,020 Approx. 17.8 hrs.	Initial NPV = -1.92 million $ Initial EUI = 59 kBtu/sqft/yer Initial SPC = 92 NPV = -5.47~-1.86 million $ EUI = 44~89 kBtu/sqft/yer SPC = 44~99 Pareto solution no. = 117

the completion of the runs, the authors provided to the designers the final trade-off analysis along with 3D design visualizations for their final decision making purposes. After the generated data had been provided more guidance was requested from the designers to discern desirable results from the abundantly populated solution pool provided by the Beagle. However, the designers indicated a positive response to inclusion of 3D imaging of all the design alternatives along with the energy performance feedback, which was not available through their prior experience with either in-house analysis or through the MEP consultant. As a result, the designers were able to include aesthetic preference as part of their trade-off analysis when examining the generated results.

Case Study II: Design Studio Based Project

In Case Study II an architectural design student was provided a single family residential design problem located along Wonderland Park Avenue in Los Angeles, CA. The program requirements for the single family residences are designated as including: 4 bedrooms, 3 full bathrooms, 2 car garage, and living, dining, and kitchen areas not to exceed a total of 3,000 sqft. All room areas are subject to designer preference, with a maximum being placed on bedroom dimensions as not to exceed 20'x20'. A 10' set back from all site boundaries is also specified. The overall design goals are defined to include a meeting all design requirements combined with consideration for a maximum decrease in energy consumption. The designer for Case Study II is a master architectural candidate with 6 months instructional experience in use of Revit but no prior experience of actual application of Revit to a design project or parametric design in general. The designer's prior environmental design experience is limited to the building physics context within the typical architectural education curriculum with no environmental simulation tool use experience or as part of the design requirements typical to her studio design briefs.

For Case Study II the EEPFD development and research team acts as both owner and consultant, providing all necessary project requirements and technical support as needed. After the determination of her design intent to explore shading, opening and each space's spatial compositions through the parametric model, the designer then proceeded to define the parametric model in Revit according to the proposed parameterization logic and initial design concept. The final parametric model is illustrated in Figure 3 and was generated over the course of 2.5 months. This recorded time includes the designer's required time to familiarize herself with the use of Revit for conceptual design through a trial and error period. As one of the goals of this case study is to observe the ability of a designer to translate their intended design concepts into a parametrically oriented mathematically defined form, the designer was asked to avoid any geometric simplifications from their original design geometry for the purposes of expediency. As such the complications of the original design geometry and the designer's unfamiliarity with parametric design and use of Revit in application to parametric design can be considered as contributing factors to the extended experienced parameterization process. Another contributing factor can be identified in the trial and error period necessary to define the design's constraint file so as to maintain both design intent and model robustness during the optimization process as the current version of H.D.S. Beagle will terminate if the geometry breaks.

Figure 3 illustrates the collected data and resultant solution space in a quantified format for Case study II. A total of 1,010 design alternatives were generated over the course of 17.8 hours. After all data had been generated, the designer did not limit their analysis to the design alternatives receiving the highest ranking from the provided data set. Instead, the designer proceeded with their own design decision making strategy, taking into consideration the context of the generated solution pool. Overall the generated solution pool through EEPFD provided an improvement in EUI from 59 to 44 kBtu/sqft/yr , in NPV from -2.92 to -1.86 million dollars, and in SPC from 92 to 99. From the full data set the designer first narrowed the solution pool according to EUI performance. The solution pool was then further narrowed to only include design alternatives with an SPC score greater than 95. From this narrowed solution pool the final design was selected based on aesthetic properties through the designer's analysis of the provided 3D images of each design alternative. The objective scores of the final selected design were: NPV = -2.38 million dollars; EUI = 52.04 kBtu/sqft/yr; and SPC= 99.29. Once this final selection was made, the designer proceeded to the next stage in design development with the generated Revit massing model. In this case study, despite the dominance of aesthetic preference as the determining factor for the final design, an improvement in all three objective scores over the initial design was observed.

CONCLUSION AND DISCUSSION

EEPFD is a framework that provides a new method of applying MDO techniques through a customized GA to integrate previously inaccessible performance feedback into the early stage building design process. While EEPFD has been validated through tests of accuracy and efficiency, the development of best practices through the key metrics of interaction, communication, and designer ease of use is the focus of continued research. Bridging the gap between the energy domain and geometric exploration remains the motivating challenge of the research that begins to address the previously established gaps. Secondary contributions of this research include the demonstrated usability of EEPFD by designers through direct interaction during the early stages of design. This addresses in part the disconnection of domain expertise as an issue for the integration of energy simulation for early stage design. Through a comparative study of the two processes implemented in the case studies, with specific focus on observing the interaction between designers an EEPFD, several general observations can be made. First, in both cases, designers were observed to have difficulty with translating their design intent into a viable parametric model. This may in part be due to unfamiliarity with both the design platform, and parametric modeling and parametric design methods. While these issues remain, they may be mitigated through increased experience and industry trends indicating an increased used of parametric design. Secondly, while the designers in both case studies acknowledged the potential applicability of the EEPFD generated results, Case Study II utilized the results in both steps 1 and 6 more completely. In Case Study I, a net zero energy building objective was desired, and therefore the scope was an over extension of the capabilities of the current form of the prototype used by EEPFD. Of particular note, there is a need to include daylighting strategies as part of their analysis. In the current implementation of the EPFD daylighing is aggregated within the more generic EUI calculation handler GBS. As a result Case Study I was not able to fully utilize the generated solution pool, however the framework as it is intended is extensible and conceived to include other tools and design objectives. Finally, in both case studies the generation of unexpected results occurs in part based on the designer provided parametric ranges and there lack of expertise in design intent to parametric modeling transcription. In Case Study I this led to undesirable window sizes, in Case Study II this led to undesirable ceiling heights. Since EEPFD possesses neither aesthetic preference nor prejudice when generating design alternatives, consideration must be made when formulating the parametric model for maintaining of design intent or an exhaustive exploration of design alternatives is desired. It can be noted that EEPFD is adaptable to either scenario, broad or specific, dependent on designer preference. Overall, in both case studies the final result was observed to be a broader based design solution pool with an overall improved multi-objective performance to enable more informed design decision making inclusive of a more expansive simulated aesthetic and formal range. While these case studies provide initial observations regarding the impact and interaction of EEPFD on the early stage design process when implemented through the designer, a subject for future research is the engagement of a more extensive experimental user group so as to further observe the impact of EEPFD on the design process. Another subject for future research is the inclusion of additional performance considerations, such as structural and daylighting, so as to meet the complexity demands of design problems through applied MDO.

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Cloud-Based Design Analysis and Optimization Framework

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Abstract. *Integration of analysis into early design phases in support of improved building performance has become increasingly important. It is considered a required response to demands on contemporary building design to meet environmental concerns. The goal is to assist designers in their decision making throughout the design of a building but with growing focus on the earlier phases in design during which design changes consume less effort than similar changes would in later design phases or during construction and occupation.*
Multi-disciplinary optimization has the potential of providing design teams with information about the potential trade-offs between various goals, some of which may be in conflict with each other. A commonly used class of optimization algorithms is the class of genetic algorithms which mimic the evolutionary process. For effective parallelization of the cascading processes occurring in the application of genetic algorithms in multi-disciplinary optimization we propose a cloud implementation and describe its architecture designed to handle the cascading tasks as efficiently as possible.
Keywords. *Cloud computing; design analysis; optimization; generative design; building performance.*

INTRODUCTION

During the last decades an increased emphasis on parametric design approaches is noticeable in early architectural design phases. One of the opportunities of parametric design is that it is possible to generate many instances of a model described in a parametric model system, allowing the exploration of a large number of design variations. The challenge is that it is not possible to examine all these design variations thoroughly enough to determine which ones to develop further. Therefore, integration of performance evaluation into the design process during early stages could help supporting the selection process of high-performing design variations. Obviously, the aim is to enable designers to make important decisions about their designs when they have most impact on performance of the building and least impact on implementation effort. Achieving the best possible overall performance of a project will allow a response to the challenges posed by climate change, resource depletion, and unequal distribution of opportunities across the globe.

CHALLENGES

This paper presents work towards an implementation of a design performance optimization framework that over time attempts to respond to as many of the following challenges as possible (Mueller et al., 2013).

1. Interoperability: the building design software industry is similarly fragmented as the building

industry at large. There are many incompatible software programs and data formats. Various approaches have been proposed to overcome or bypass this obstacle to seamless collaboration between design team members (Flager et al., 2008; Janssen et al., 2012; Toth et al., 2012).

2. Data equivalency: design tools may not have sufficient capabilities to create all data required by analysis tools.
3. Data discrepancy: conceptual design is less concerned with the detailed information required by analysis software (Bleil de Souza, 2012). Therefore, analysis opportunities in early design may be limited by the information available to the design team or made available by the design team.
4. Speed of feedback: design is an iterative process, with fast and frequent iterations. Analysis feedback into these design iterations has to be fast enough to remain relevant for the current iteration (Hetherington et al., 2011).
5. Performance proxies: there is only insufficient research to permit use of performance proxies to bypass lengthy execution times of established analysis methods. Performance proxies could use either simplified analysis methods, or simple analyses of a different type indicative of future performance.
6. Results display: visualization of analysis results is not visually related to the geometric model (Dondeti and Reinhart, 2011). This prevents designers from quickly gaining insight into where in the design deficiencies are located and thus delays or prevents design improvements through human intervention in reaction to analysis results.
7. In-context results: analysis results are not available in the digital model for access that would enable automation of refinement iterations or multi-objective optimization routines.
8. Human-machine balance: not all design goals are measurable. How are "hard" computed performance metrics balanced with "soft" qualitative aspects. Several approaches are conceivable, including a mix of automated iterations and iterations performed by the design team (Geyer and Beucke, 2010).

FIRST PROTOTYPE

The proposed system is composed of an analytic framework which connects tools used to generate design or analysis models (authoring tools) on one side and analysis or simulation tools (analysis tools) on the other side and of an optimization framework which connects the design and analysis system to optimization engines. Initially the data flow uses a mix of proprietary and publicized file formats. The specific components in the prototype implementation are:

- GenerativeComponents (GC) [1] as parametric design authoring tool with add-ins extending GC's classes with structural and energy model components;
- STAAD structural analysis engine [2];
- EnergyPlus analysis engine [3];
- DARWIN optimization framework including two genetic algorithms [4]; and
- Bentley Analytical Services Framework (analytic framework).

The utilized file formats are:

- EnergyPlus's IDF file format for energy model information sent from GC to the analytic framework;
- STAAD.Pro's STD file format for structural model information;
- GC's GCT file format for parametric model information;
- XML file format for extraneous process information;
- TXT file format for extracted results.

This solution was introduced and tested at the SmartGeometry event in 2012 in Troy, NY [5] in a prototypical implementation (Mueller et al., 2013). It included energy analysis and structural analysis plus a genetic algorithm (GA) (Figure 1). All of the system architecture was implemented on a client system (desktop computer). The analysis engines were also implemented as analysis services on the cloud with

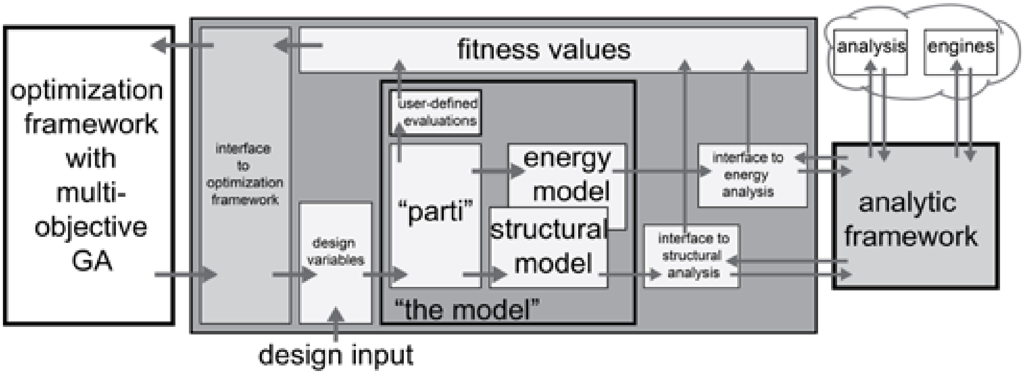


Figure 1
Software architecture for the prototype implementation at SmartGeometry 2012 with only the analysis engines in the cloud.

the analytic framework establishing the connection between the client and cloud applications based on user selection of "local" or "cloud" execution of analysis.

Limitations of this test implementation were: the implementation did not progress beyond prototype stages causing several deficiencies; analysis models were kept at the minimal implementation necessary to allow the analysis algorithms to execute while possibly achieving sufficient completeness of the models for conceptual design; there was only a partial deployment of the system in the cloud, particularly of the analysis engines, leading to accumulated latency issues; and lack of robustness. The conclusions of this prototype implementation were:

- Increase robustness of the software components and their communications.
- Increase "completeness" of analysis and simulation models without increasing required model complexity.
- Develop the system architecture in a way to minimize negative side-effects of a deployment in the cloud while maximizing the desired positive effects.

SECOND VERSION OF ANALYSIS AND OPTIMIZATION FRAMEWORK

The improved second version of the analysis and optimization framework responds to the limitations by replacing the prototype optimization framework with a version rewritten to meet production-level software standards, including replacement of the GAs with ones that have been in commercial use for several years, extending them to multi-objective optimization while still complying with production-level software standards. This includes use of inter-application communications that are robust, secure, and prevent the problems encountered with the prototype. Most importantly in the context of this paper, this second version of the design analysis and optimization system includes all necessary components running as services on the cloud (Figure 2).

User Workflow and Software Components

On the surface, the user workflow and involved components are the same as in the previous implementation: the user designs a parametric model including analytical model components in GC. The model needs to be driven by parameters so that changes to the model can be applied in response to analysis results or any other computations evaluating the performance of the current instantiation of the parametric model (Mueller et al., 2013). The analytical model components provide input to analytical nodes which connect to external analysis engines (STAAD and EnergyPlus) via the analytic framework. Analysis results are returned to the parametric model for any subsequent computations to extract or determine characteristic performance values. These are passed as fitness values to an optimization node in GC.

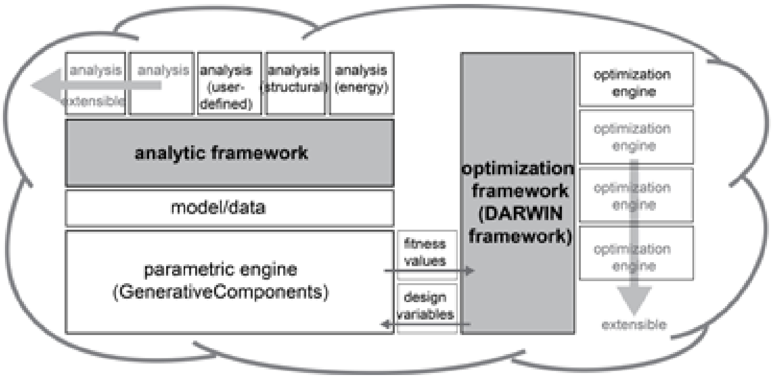


Figure 2
Cloud components of the software architecture for the improved implementation.

The optimization node in GC is the interface to the optimization framework which in turn interfaces with the optimization engine. The user also identifies those parameters or design variables that the optimization process may manipulate. The optimization framework converts parameter ranges and their discrete increments (resolution or granularity) into binary chromosomes (or the genome) for the GA in order to generate individual design solutions or phenotypes in analogy to evolutionary processes in nature.

MDO Process

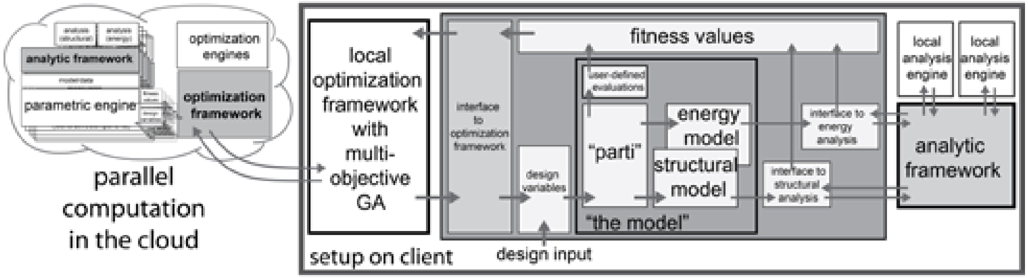
When the optimization process starts, the GA generates a first set of chromosomes to create a first generation of individuals (a generation's population) based on the GA's implementation of stochastic principles applied to an evaluation of the nature of the genome. The optimization framework interprets the chromosome into the set of design variables or parameters and pushes those into GC as engine for the parametric modeling service with the applicable parametric model active. The parameter changes propagate through the model to create the corresponding model instance (individual or phenotype).

Any analyses included in the model are requested as cascading processes via the analytic framework while the parametric modeling engine waits for the results to return, fully dependent on successful termination of the analysis processes. It then performs any subsequent computations, resulting in fitness values for the specific phenotype that are fed back into the optimization node and from there to the optimization framework. The fitness values are associated with the specific individual's chromosome and communicated back to the GA. Once the GA has received all fitness values for an entire population it evaluates that population in order to determine those sets of chromosomes that it will use to generate the genome for the next generation, i.e. the next set of genotypes.

When the optimization is processed locally on the client computer, the optimization framework pushes each phenotype's chromosome into the parametric modeling engine and then waits for the corresponding fitness values, which means that all processes are executed sequentially, starting with the parametric model update, including the analysis requests and subsequent evaluations, and ending with the return of fitness values to the optimization node. This repeats for each individual in a generation until the entire population is processed. After the GA evaluates the results for the generation it creates a new set of genotypes for the optimization framework to start the process for the next generation.

When the user requests execution in the cloud, in contrast to the prototype this implementation processes an optimization request entirely in the cloud. The user designs and develops the paramet-

Figure 3
Software architecture of client and cloud components of improved implementationes.



ric model, the connection of salient parts of the model to various types of analyses, further evaluation computations, and the workflow connection to the genetic algorithm in the authoring tool GC on a desktop computer (the client) (Figure 3). This avoids internet latency while modeling and permits local testing and debugging of the parametric model, its connection to the analysis engines, and validation of additional computations performed on analysis results for their use as fitness values in the GA process.

When the user commits the optimization process to the cloud the request is packaged with all required parameters for the optimization process itself, like population size and termination criteria; the required data, especially the parametric model as a snapshot GCT file; the composition of the parameter set (names, ranges, resolution); and other required information not relevant in the context of this paper. This package is sent from the optimization framework client to the optimization framework's web service in the cloud which then creates an optimization job based on the information received in the package. Most important for the cloud implementation, the optimization framework permits to dispatch all phenotype requests for a population in parallel, while generations have to be processed sequentially. This allows parallelized evaluation of all individuals in a generation and potentially accelerates processing by a factor close to the population size specified by the user for the optimization process.

CLOUD IMPLEMENTATION

The cloud implementation uses Microsoft's Azure [6]. "The Cloud" as a concept assumes as primary benefit virtually unlimited processing resources in form of virtually identical work horse CPUs (compute nodes) with some amount of RAM and high connectivity to the respective cloud infrastructure in the physical server farm in which they are housed. Of course, there are other benefits to using cloud resources, e.g. ubiquity given internet connectivity with sufficient bandwidth, or availability without first cost of ownership or maintenance costs even when not used. These are secondary to the issues addressed in this paper. Relevant is another premise of the cloud, which is that these resources are state-free, which correlates to the assumption that any user of these resources needs to be prepared that they could fail, go off-line, or be replaced at any point in time. Cloud processes (cloud services) must not rely on preservation of state over long time. They should be set up to receive processing requests, perform the necessary computations, potentially store any results in a pre-determined location, potentially indicate successful termination in addition to depositing the successful results, and terminate. Requestors of cloud processes should be prepared that any started process may fail and that requests may have to be re-issued until successfully resolved.

Compared to the implementation on a desktop computer, a cloud implementation therefore introduces additional elements: first and foremost is a scheduler which receives requests to process com-

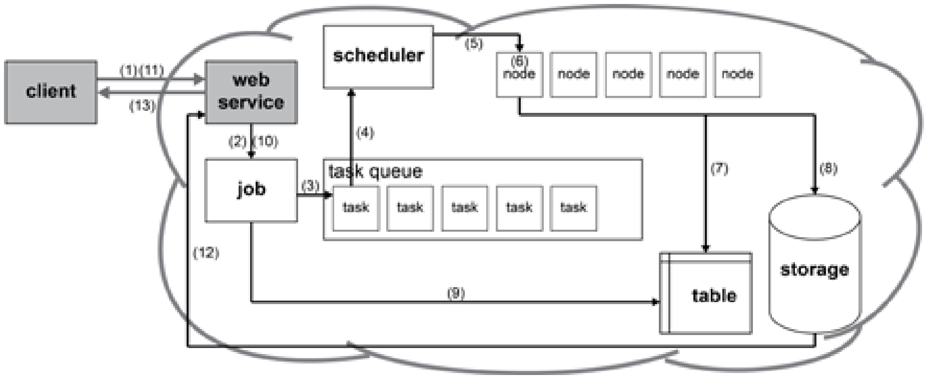


Figure 4
Simple cloud scheduling service schematic.

putational tasks and dispatches them to available compute nodes [7] (Figure 4).

"Simple" Cloud Task Scheduling

The sequence of cloud processing is that a client requests a processing job from the client-facing web service of the cloud (1). The web service starts the requested job (2). The job generates as many tasks into the task queue as needed (3). The scheduler polls the task queue regularly (4) and pulls the first queued task and distributes it to an available compute node (5). The task processes on the compute node (6), retrieves any data it needs from storage usually via look-up in some table or database, posts or updates any task states to a table (7), and returns any process results to storage (8). It indicates its orderly termination to the scheduler. The job process polls the table (9) to assess progress of individual tasks or the overall job status. The web services polls the job for job progress or completion (10). On request from the client (11), the web service pulls any results from storage (12) and displays them to the client (13) or makes them available for download to the client. Compute node fail-over is implemented by the scheduler hiding a task that has been distributed to a node. A time-out limit makes visible any hidden task that has not indicated orderly termination to the scheduler within its time-out, so that the scheduler will distribute it again on the assumption that the computation failed for one reason or another, including failure of the respective compute node.

This is a very straightforward implementation for massively parallel processing tasks ("embarrassingly parallel") which are the ideal use case for the cloud. However, the most important implication of this type of cloud scheduling regime is that task sequencing as required for the MDO process cannot be guaranteed, so that process dependencies need implementation of specific measures to ensure proper sequence to avoid extended wait times in the best case and deadlock in the worst.

MDO Cloud Process

For the multi-disciplinary optimization case there are various levels of dependencies that might suffer substantially from the "state-free" and fail-anytime premise of cloud resources. If the task is the optimization process itself, then any failure during the process will void the entire process and requires the entire optimization to restart. This suggests that the optimization framework would need to be state-aware. Similarly, the optimization engine (depending on its architecture) needs to be state-aware or needs to store its intermediate results in such a way that it could pick up the process at any point, perhaps from conclusion of a generation. Any parametric model (e.g. individual in a population) is of course one of the parallel processes in a generation that benefits from the virtually unlimited resource concept of the cloud. However, during several as-

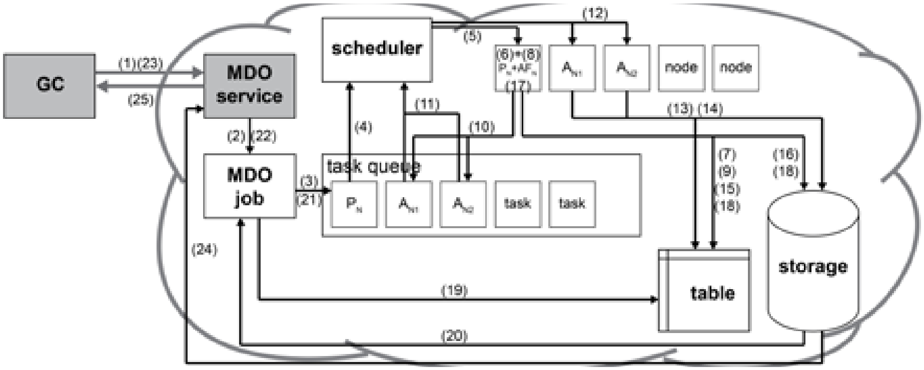


Figure 5
Cloud scheduling service schematic for MDO services.

pects of the MDO process various states are reached in conflict with the state-free concept. This requires some additional steps in the process sequence in order to be handled by a standard scheduler.

MDO Cloud Task Scheduling

An improved system of MDO cloud task scheduling is used to overcome the issues described above (Figure 5). It uses tables to preserve states in an otherwise state-free system that can fail at the parametric model and analysis level. Model generation and analysis tasks are executed “in parallel”, with the analytical framework as part of the parametric model task (i.e. on the same node, because these processes are sequential anyway). However, the analytical framework can start one or multiple analysis tasks that will be queued and handled by the scheduler. Possible approaches are single-queue or dual-queue, separating modeling and analysis tasks. The advantage of a dual-queue system is that it could be designed to handle cascading dependencies without any danger of resource deadlock; however, its implementation is more complex. The current implementation uses a single task queue for both, modeling and analysis, tasks and is based on the premise that adaptive scaling (marshalling of additional resources when tasks are waiting in the queue) will prevent resource deadlock.

The sequence of the MDO cloud processing is that the GC client requests an MDO job from the MDO web service on the cloud and sends the required data package (1). The MDO web service starts the MDO job (2). The MDO job comprises the optimization framework and the optimization engine (the GA). It extracts and applies or distributes the relevant data from the data package, handles the parameter set to chromosome conversion, etc., generates all parameter sets for a generation, and generates phenotype tasks P_N into the task queue. The scheduler polls the task queue and pulls task P_N (4) for distribution to compute nodes (5). The P_N task processes the appropriate parameter set (phenotype) in an instance of the parametric modeling engine (GC) on the compute node (6) and posts or updates its execution state to the table (7).

When the parametric model includes analysis nodes, these request analysis tasks from the analytical framework instance AF_N which runs on the same node as the parametric model engine (8). This does not impact processing speed because the parametric model engine needs to wait for the cascading analysis processes to terminate and for the analytical framework instance to return the analysis results. The analytical framework instance AF_N posts and updates any processing states in the table (9) and adds analytic tasks A_{N1} and A_{N2} (etc.) to the task queue (10). The scheduler pulls the analytic tasks A_{N1} and A_{N2} (etc.) from the queue (11) and distributes them to available compute nodes (12) where they start processing, pulling any data from storage, updating

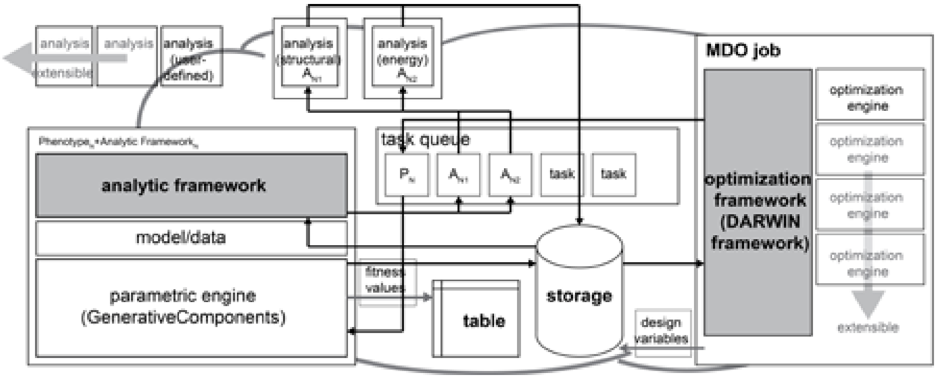


Figure 6
Cloud software architecture including the additional task management elements.

their processing state to the table (13), and depositing any results back to storage (14).

Meanwhile, analytic framework instance AF_N polls the table for the analysis tasks' states (15), and when they have successfully terminated it pulls the results from storage (16). The analytic nodes in the phenotype task P_N in the parametric modeling engine poll process AF_N for analysis results and post-process them to convert them into fitness values (17). P_N also computes any other fitness values and passes them to the optimization node in the parametric model. The optimization node passes the fitness values to an optimization framework instance on the compute node which posts the results and task completion to storage and table, respectively (18).

The optimization framework instance in the MDO job polls the table for completion of all tasks P_N in a generation (19), and pulls the fitness values from storage (20). The optimization framework in the MDO job prepares the generation data for the GA which then generates the next generation's parameter set and starts scheduling a new set of phenotype tasks P_N (21). The MDO service polls the MDO job for completion of the entire optimization run (22) and notes completion, if applicable. The optimization framework client polls the MDO service for job completion (23). Upon request, the MDO service pulls the optimization results from cloud storage (24), and the client downloads them (25) in order to display them in the client context and/or instantiate the corresponding solutions.

CONCLUSION

Cloud computing provides access to ubiquitous and virtually unlimited resources. It permits acceleration of processes that include tasks that can be performed in parallel but are predominantly performed sequentially in conventional desktop implementations. As demonstrated, even more complex processes like multi-dimensional optimization can be successfully handled with basic task scheduling if any cascading and dependent tasks are set up in ways that allow the proper management of sequencing (Figure 6).

Even though cloud resources need to be accessed through internet connections and the computational resources available in the cloud are consumer grade rather than high-end, cloud computing is advantageous whenever massive parallelization of tasks can be utilized. In the case of MDO using GAs, it is obvious that the individuals in a generation can be processed in parallel leading to acceleration of the process by approximately the population size. In addition, any analysis processes included in the MDO job could be processed in parallel, leading to additional time savings depending on the number and length of the analysis processes.

The cascading nature of the processes and their dependency pose a difficult challenge if in contradiction to the base premise of virtually unlimited resources, the computing resources are artificially limited, e.g. if for an MDO job that includes analysis tasks fewer compute nodes are allocated than the population size in a generation. This would cause an irresolvable deadlock of resources because the parametric modeling or phenotype processes would occupy all the available compute nodes and any remaining phenotype tasks as well as the cascading analysis tasks would be queued up without any chance of additional nodes becoming available. If the set up on the cloud permits limitation of the number of compute nodes additional precautions need to be put in place to reserve compute nodes for cascading processes.

FUTURE WORK

With completion of the improved implementation imminent, use of the system in user case studies is next. This will also allow benchmarking of desktop implementation and cloud implementation to assess the impact of parallelization using "virtually unlimited" resources. Additional work will be documentation and publication of APIs to allow third party development to add analysis engines and optimization engines, as well as, add-ins for design authoring tools to connect to the optimization framework.

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Graphical Smalltalk with My Optimization System for Urban Planning Tasks

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Abstract. *Based on the description of a conceptual framework for the representation of planning problems on various scales, we introduce an evolutionary design optimization system. This system is exemplified by means of the generation of street networks with locally defined properties for centrality. We show three different scenarios for planning requirements and evaluate the resulting structures with respect to the requirements of our framework. Finally the potentials and challenges of the presented approach are discussed in detail.*
Keywords. *Design optimization; interactive planning support system; generative system integration; evolutionary multi-criteria optimization.*

MOTIVATION

For many computer scientists the programming language Smalltalk was the most pioneering human-computer interaction language of the 1970s. It was designed to be so simple that even children could program. It is one of the first totally object oriented languages – everything is an object. While today many ideas from Smalltalk have since been adopted by other languages, the visionary thinking of the time when it was developed can still inspire us today to strive for flawless human-computer interaction in the development of design optimization systems for architecture and urban planning.

PROBLEM STATEMENT

A number of promising generative algorithms are available today, but none are currently employed to enhance and simplify the day-to-day work of urban planners. Computer support for urban planning projects is usually restricted to basic CAD drawing tools. In the authors' opinion, one reason for the lack of integration of generative methods in planning processes is their complicated handling. Typically they require extensive input of abstract technical rules and parameters that are unfamiliar and daunting for planners.

The situation is further complicated by the fact that planning projects typically consist of a mixture of contradicting and non-contradicting criteria as well as of directly measurable criteria and only indirectly interpretable measures. The lack of suitable optimization methods hinders a systematic evaluation of possible compromises between contradicting planning requirements.

STATE OF THE ART

In their seminal book, Radford and Gero (1988) show various examples of how optimization strategies can be used to solve design problems. Although today we can use more flexible evolutionary optimization methods (Deb, 2001), the concept for their applica-

Figure 1
Planning scenario divided into three levels of abstraction. Left: Topological relations between elements and basic properties. Centre: Geometric distribution of the elements. Right: Geometric representation of a possible planning solution [6].

tion and the role of pareto-optimal fronts has not changed a lot over the past few decades (Bentley and Corne, 2002). A good example for state of the art interactive generative planning systems is the work of Derix (2009). Dillenburger et al. (2009) have also presented an interesting system for creating building designs using a weighted-sum optimization algorithm.

Current commercial solutions for generative or procedural modeling, for example Grasshopper [1], GenerativeComponents [2], or CityEngine [3] exemplify the problems with such systems: they require intensive training before they can be used efficiently and though sometimes attractively designed, their user interfaces are not intuitive for urban planners. Furthermore it is not efficient to couple them with optimization tools, because of the increased computing time and restricted possibilities offered by their corresponding APIs. Although Galapagos [4] provides an optimization method for Grasshopper, Rutton (2010) notice that it is only useful for simple problems.

AIMS

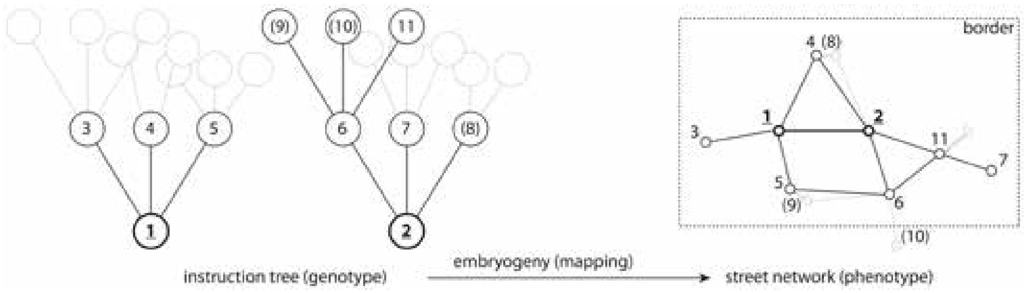
Our main goal is to use graphical objects to represent a planning problem and to control an optimization algorithm using primarily these objects. A further challenge is to translate the planner's partially vague qualitative requirements into a precise quantifiable problem representation for an algorithm. Translation problems are one reason why planners rarely embrace computer support. To improve this situation we aim to develop an interactive system for supporting the urban planning process with a more constructive and intuitive interface for planners. The combination of well-designed interaction strategies and planner-friendly problem representation as a basis for evolutionary optimization strategies is as an issue that is yet to be resolved.

CONCEPTUAL FRAMEWORK

To address the aforementioned problems, our first task is to develop a conceptual framework that includes a combination of various interaction strategies for the user interface, different generative techniques, and some optimization methods. We have approached this concept from two perspectives: from that of a planner and from that of a software developer.

To meet the planner's requirements we separate the problem representation and the definition of requirements by at least two levels of abstraction (Figure 1): The first holds the topological relations between various elements and basic properties (Figure 1 left). The graphical objects on this level can encode parameter values e.g. by their size, position or colour, etc. The second abstraction level comprises the geometric representation of possible planning solutions (Figure 1 right). One can interact with all the graphical objects of a current planning proposal on each level to test different options and to refine a planning iteratively. From the software developers point of view we develop a framework for combining evolutionary optimization techniques. These include generative algorithms and evaluation mechanisms to analyze the generated variations. As a basis for this framework, we use state-of-the-art evolutionary multi-criterion optimization methods. For a comprehensive and easily understandable introduction to evolutionary algorithms, see Bentley and Corne (2002). In the following description, we focus only on the essential aspects that are necessary for our purposes. We take the AForge.Net Framework [7] as the starting point for the implementation of

Figure 2
Mapping process from an instruction tree to a street network. The grey dotted street segments on the right side illustrate the adaption of instructions how to add a new segment to a existing network.



our evolutionary algorithm (EA). The main argument for EA is their flexibility in dealing with the problem representation, which is crucial for the problems described above.

From the user's perspective we reverse the logic of generative planning systems: instead of exploring the results of different parameter settings or procedural rule sets, we allow a planner to graphically define what performance a solution shall have and the optimization system automatically generates a set of best compromise solutions. This constellation of deducing a solution from its desired properties is called an inverse problem [5], which was used with a different intention by Koltsova et al. (2012). Based on this concept we develop a method that can be called bi- or multi-directional planning, since one can control a computer-based planning system from any of the abstraction levels as shown in Figure 1.

IMPLEMENTATION

In this paper we present just one part of the aforementioned framework: the optimization of a street network inside a planning area with specific local properties. The sub-areas can be defined by a user with the help of graphical objects in a similar way as shown in Figure 1.

Before we consider some example applications of the optimization system, we first describe the implementation of its basic generative and evaluation mechanisms. Taking the AforgeNet Framework [7] as our starting point, we extend it by a class for a chromosome with mutation and crossover methods and a class for a customized fitness function as described below.

Generation Mechanism

The basic idea for the generative mechanism is to use an instruction tree, which holds the instructions on how to grow a street network (Figure 2). This growth process can be denoted as embryogeny and is responsible for unfolding the abstract information stored in a genotype to the concrete structure of a phenotype, which is why this process can also be described as mapping from genotype to phenotype. For the genotype representation we use a chromosome which in turn is represented in our case by an instruction tree as shown in Figure 2. The rules to create the street network (Figure 2 right) are adapted from the concept of self-sensitive L-Systems by Parish and Müller (2001).

As a basic component of the instruction tree we implement a class for an individual instruction node which stores the information on how to add a new street segment to an existing node of the network (Figure 3). The instructions for a node are reduced to three which is the minimum necessary for our basic system: the range li for the length of a street segment, the angle ai that indicates the angular deviation from a regular division, and the range κi of possible arms at a crossroad. Figure 3 illustrates the mapping of the instructions of three instruction nodes to a phenotype representation. We use the additional parameter tree depth to restrict the size of an instruction tree to a certain limit. The individuals of an initial generation of a population start with randomly assigned instruction values.

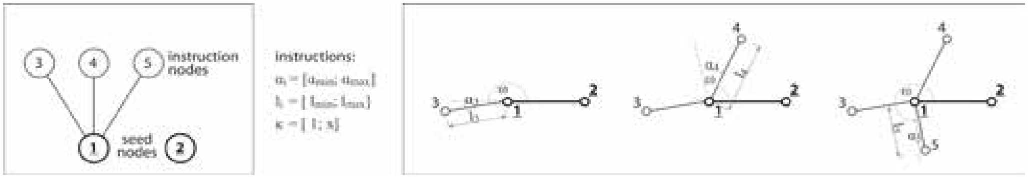


Figure 3
On the left, the tree shows the main instructions of an instruction node. In the box on the right one can see how the instructions are assigned to a street network.

The instruction tree can be mutated and used for crossover operations as illustrated in Figure 4. Since the instructions of a node are always relative to the existing street network, new combinations after the crossover always work. The main reason why we use a tree structure for the chromosome is that it ensures that after the crossover and mutation operations, the corresponding street network remains connected (if the initial network was connected). The mutation operator simply takes (e.g. 1-10%) individual nodes of an instruction tree and assigns a randomly generated value to one of its parameters. The frequency of the execution of these operators at one iteration (or generation) is defined by the crossover and mutation rate.

One of the most important properties of a generative mechanism, as part of an optimization process, is its ability to generate very different network topologies. It is this property that allows an optimization system to find interesting and surprising solutions for a given set of restrictions and goal functions.

Evaluation Mechanism

As a goal function (or fitness function) for the evaluation of the generated street network we use the betweenness centrality (choice) of a network. For this we need to calculate the all-pair shortest paths for the network, and compute this following the concept elaborated by Hochberg [8] using a parallel GPU implementation of the Floyd-Warshall algorithm to calculate shortest paths. For the weightings in the corresponding graph we use angular distances instead of metric distances as introduced by Turner (2001; 2007). The choice value for a specific street segment equals the number of shortest paths from all street segments to all others that pass through that segment. For the sake of simplicity, we use only the choice value in the following examples to characterize street networks, but other centrality measures would be useful too.

EXAMPLE SCENARIO

As a starting situation for the following examples we use an area with the dimensions 3000m × 2000m that needs to be filled with streets (Figure 5). The positions of the existing street connections are marked by nodes with underlined numbers. The areas defined in the right-hand image in Figure 5 will be used in later examples to define a central sub-area (red, dashed) and a quiet sub-area (blue, checked). The red center is placed near the coordinates

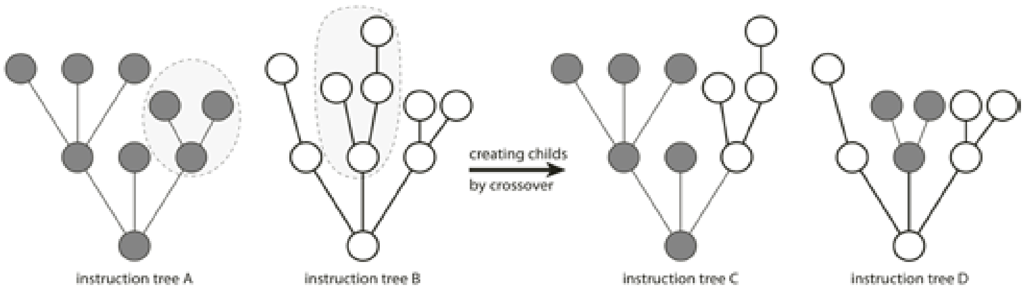
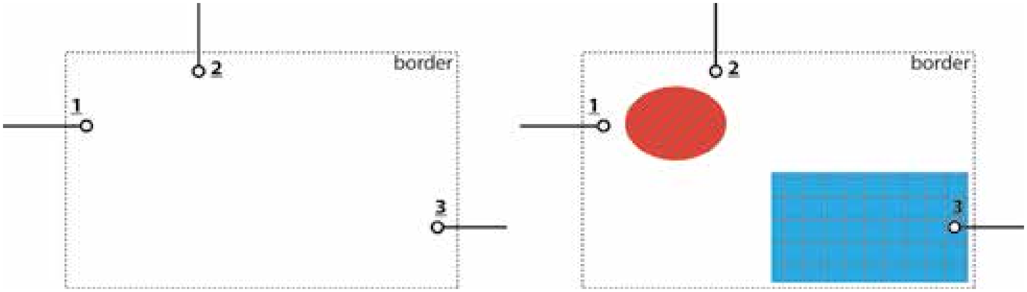


Figure 4
Creation of new child variants (C and D) by a crossover operation applied to two parent instruction trees (A and B).

Figure 5
Initial planning situation: The border defines the planning area, and connections to the existing street network are represented by the nodes with underlined numbers. The coloured areas in the right-hand image denote areas where the new street network will have defined properties.

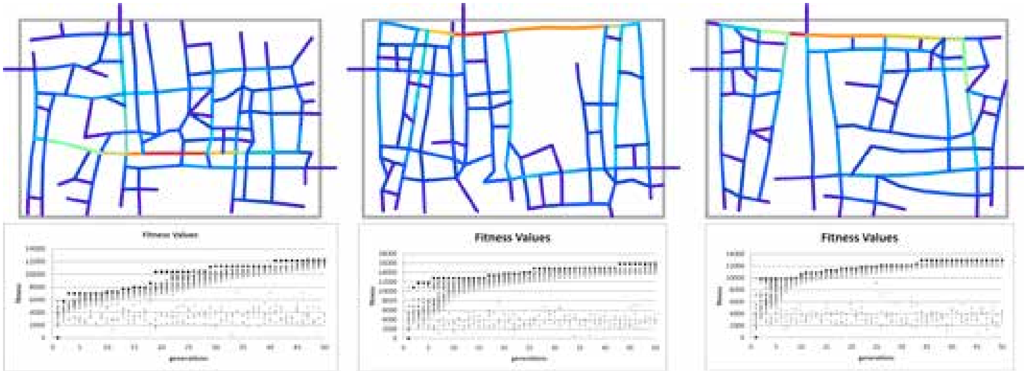


750m/1500m (coordinate origin in the left bottom corner) while the blue quiet area fills the bottom right-hand quarter of our planning area. For the following examples we use the following initial parameters: generations = 50, population size = 50, mutation rate = 0.25, crossover rate = 0.75, tree depth = 8. It is import to select a tree depth high enough to ensure that the complete area can be filled with streets and that there is no indirect restriction for the optimization algorithm. The values for the nodes of the initial instruction trees were initialized with random values with the intervals: αi =[-10, 10], *li* =[10, 40], κi =[1, 4]

First we consider a simple basic example scenario, where we use the aforementioned optimization method to maximize the maximum choice value (Figure 6) and the sum of all choice values of the generated street network (Figure 7). We start with an empty area as shown in Figure 5 on the left. Figure 6 and Figure 7 show three resulting street networks with the corresponding diagram of the development of the fitness values.

To achieve very high choice values, the most obvious strategy is to design a network, that is separated into two parts which are connected by the most used street, the one with the highest choice value. In cities we find this situations, for example, in places where a bridge crosses a river or a narrow valley divides a settlement. If we consider the three street networks in Figure 6 we can see this structure in the network in the right-hand image. Of the three networks in Figure 6, however, the network in the middle has the best fitness value, although there are no two separate parts. This results from the fact that for the calculation of the trips we use the shortest angular distance and not the shortest metric distance. Because of this, there is one street segment at the top-center which is used very often. If we look at the

Figure 6
First example scenario. For each of the street networks shown, the maximum choice value is maximized. Red represents street segments with high choice values and blue low choice values. The diagrams in the bottom row show the development of the fitness values over 50 generations.



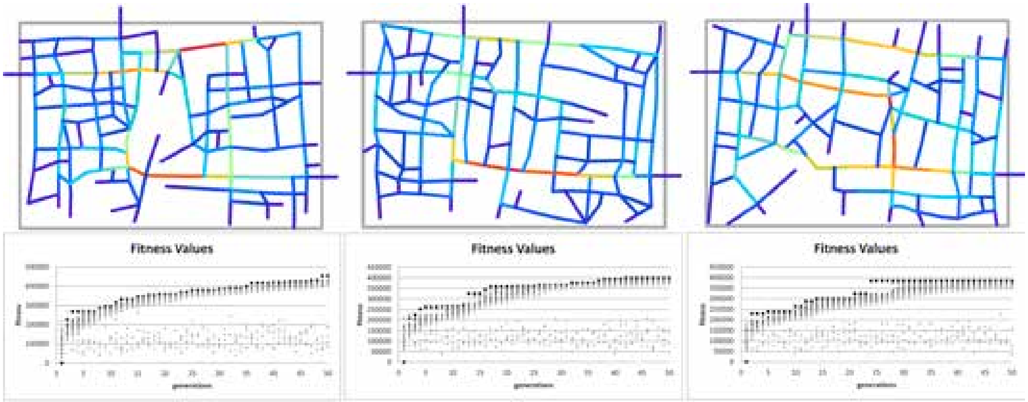


Figure 7
Second example scenario: For each of the street networks shown, the sum of all choice values is maximized. Red represents street segments with high choice values and blue low choice values. The diagrams in the bottom row show the development of the fitness values over 50 generations.

left-hand network in Figure 6 we find that there is no single bottleneck, and at least one other populated route. As a result this network has the worst fitness of the three.

The fact that the three best networks have different maximal fitness values (diagrams in the bottom row of Figures 6 and 7), indicates that the evolutionary optimization process explores different parts of the search space each time it is run. But despite the small differences in the maximum fitness values of the variants, they all fulfill the requirements relatively well. When we consider the random points (representing randomly generated variants) we can clearly see the advantage of using the evolutionary search process compared to randomly generated solutions. The best variants are improved continuously over the 50 generations and reach a level, which cannot be achieved by a random generation process.

In our second example we use the same initial scenario as in the first one, but we adapt the fitness function to maximize the sum of all choice values of the street network. The topologies of the resulting networks in Figure 7 are clearly different to those in Figure 6. Here we cannot see separate network parts and the streets segments with the highest choice values are not concentrated at one location but distributed across the network. This difference proves that our optimization system is working as expected. The development of the fitness shown in the diagrams in the bottom row in Figure 7 is similar to that of the corresponding diagrams in Figure 6. This indicates that both fitness functions direct the search process in a similarly efficient way.

Our third example is based on the initial scenario with two defined sub-areas as shown in the right-hand image of Figure 5. In Figure 8 the central sub-area is shown as a dotted ellipse and the quiet sub-area as a dotted rectangle. To include the spatial aspect in the fitness function, we have to define how to represent the graphical objects that represent the sub-areas with the corresponding specified properties.

First we consider the central sub-area. To achieve a highly-populated center in the defined sub-area we want to locate the street segment with the maximized choice value in it. Therefore we measure the distance *dcmax* of the street segment with the maximum choice value *cmax* to the center. This distance can be used as a weight so that we can decrease the fitness of a network according to the distance *dcmax*:

$$F1 = c_{max} * \left(1 - (d_{cmax}/D)\right)^2, \qquad (1)$$

where *D* is a constant which denotes the maximal possible distance. In our examples, this is the diagonal of the border rectangle *D* = 3606m.

Secondly, we consider the quiet sub-area. To achieve an area with as little traffic as possible, e.g.

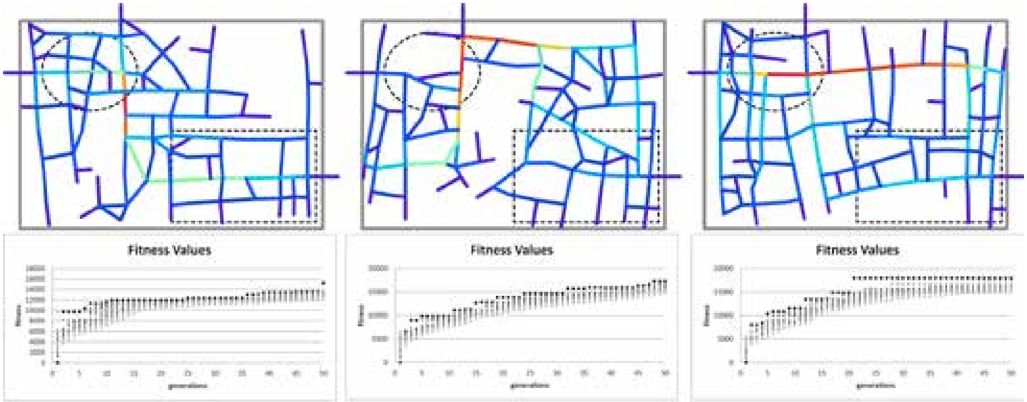


Figure 8
Third example scenario. For each of the street networks shown, we use a combined fitness function: one factor is the maximized maximum choice value that is weighted with the distance to the central area (dotted ellipse), while the second factor is the average sum of all choice values which are assigned to street segments inside the quiet area (dotted rectangle). Red represents street segments with high choice values and blue low choice values. The diagrams in the bottom row show the development of the fitness values over 50 generations.

for residential usage, we want to have only streets with low choice values in it. Therefore we sum all differences of the choice values from the street segment *ci* that are located inside the quiet area *A* and the maximum choice value of the network *cmax*. The average of this sum is used as the second part of our fitness function:

$$F2 = \left(\sum_{i=1}^{n}\left(c_{max} - c_i^A\right)\right)/n \quad (2)$$

From the two fitness values *F1* and *F2* we calculate the final fitness value as the sum of both:

Fitness = *F1* + *F2*. (3)

The street networks resulting from this optimization process are shown in the top row of Figure 8. The results fulfill both of our requirements relatively well: the red coloured street segments with maximum choice values are located close to or inside the central sub-area, while we find primarily only blue coloured street segments with low choice values in the quiet sub-area. To evaluate the effect of the defined sub-areas on the resulting street networks we can compare the variants from Figure 6 and Figure 7 with the ones in Figure 8. We can observe very different structures in comparison to the second example scenario in Figure 7 and similar structures to our first example scenario in Figure 6 showing the two separated network parts (Figure 8 in the middle). In general the results seems self-evident, but nevertheless we can see some problems, e.g. at the solution in the left-hand image of Figure 8. Here the maximum choice value is at the edge of the central area and there is a relatively populated road in the quiet sub-area. Maybe the optimization algorithm could have found a better solution with more generations. But the combined fitness function may be hindering the improvement of this variant. We will discuss this problem in the next section.

DISCUSSION

As outlined in the description of our framework, we have demonstrated a method of representing planning requirements using graphical objects that can be used by an optimization system (Figure 5). The main challenge of the system is interacting with design variants, not because of the complicated user interface – it is, for example, possible to change the genotype and thus the later optimization process by manipulating the graphical objects of the phenotype (street segments and crossroads). This makes it possible to realise a multi-directional planning method as described above.

The main problem of our system is that the optimization process is much too slow for use in an interactive process. The computation of the above examples needed 2030 minutes on an average modern notebook. One generation therefore needed half a minute: half a second would be a more acceptable timespan. Of course these times depend a lot on the size of the street network, the population size and other aspects. But the main time-critical aspect is the computation of the all-pair shortest path. This needs to be improved in future using an optimized algorithm and more powerful hardware.

In addition we use a very inefficient method to generate instruction trees. We use a random initial process which produces a very huge tree from which only a small fraction of nodes are needed to grow the street network. In the examples above, in the case of $\kappa i = 4$, we have 3^depth instruction nodes for each tree. For a tree depth of 8 this results in max. 3^8 = 6561 nodes, but we only have approximately 300 street segments. Alternatively one could create random but meaningful street networks in the beginning and encode them to make much more efficient instruction trees.

Variations of the angles and placement of the initial street segments as shown in Figure 5 have a relatively significant impact on the further growth and thus on the final phenotype of the network. Therefore, to search for optimal solutions it may also be useful to vary the initial segment.

Another interesting aspect of the presented examples is a product of the property of EAs to create their own biotope for the artificial life forms – in our case the street network. We can observe special strategies for the EA to maximize their fitness (the choice values): the first is to maximize the number of street segments to produce more trips and thus higher maximal choice values. This could be overcome by averaging the values i.e. dividing the choice values by the number of streets. The second is to generate street segments at strategically beneficial places (e.g. top left corner in the left and right networks in Figure 8). These segments can produce more trips via certain segments with high choice values to increase them further.

In our last example (Figure 8) we have used two goal functions: one to achieve a center and one to create a quiet area. Both are combined into one fitness function. Here we run into the problem of weighting both criteria against each other in a more or less arbitrary way. This weighting, however, has a significant effect on the optimization process und thus on the quality of the results. For example the optimization process can get stuck in local optima, since one criterion is already very good, but the other not. The improvement of poor criteria may be hindered because it may negatively affect other very good criteria, so that the resulting fitness value cannot be improved. To avoid these kind of problems we need to use evolutionary multi-criteria optimization (EMO) methods (Deb, 2001).

CONCLUSION AND OUTLOOK

In this paper we have demonstrated the potentials of using an optimization system for urban planning tasks using a test scenario. In this scenario we have generated street networks with defined local properties. The presented system is a first component of an framework with basic functionality to efficiently search compromise solutions for complex planning problems. A first software prototype has been implemented with an intuitive user interface to represent planning problems, to present various compromise solutions, and to improve them interactively.

The differences in the examples presented in Figures 6-8 show clearly that our system doesn't generate globally optimal solutions – e.g. one can delete connections that enable ring trips around the centre to increase the traffic through the centre (and to increase the corresponding choice value). This is an inherent aspect of EAs: they cannot guarantee finding the globally best solutions, but they can always offer good ones. This disadvantage can be improved by running more generations or by using separate populations in parallel and migrating the best variants between them. In our context, this isn't a problem because planners are not usually looking for global optima as goal functions represent only a part of a planning problem. Thus the interactive and adaptable search for variants is the main support for the planning process.

The next step for the development of our framework is to implement a more complex EMO system which integrates algorithms for parceling and building placement (Aliaga et al., 2008; Knecht and

Koenig, 2012). With this development we can achieve the multi-level approach illustrated in Figure 1.

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Evo-Devo in the Sky

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Abstract. *Designers interested in applying evo-devo-design methods for performance based multi-objective design exploration have typically faced two main hurdles: it's too hard and too slow. An evo-devo-design method is proposed that effectively overcomes the hurdles of skill and speed by leveraging two key technologies: computational workflows and cloud computing. In order to tackle the skills hurdle, Workflow Systems are used that allow users to define computational workflows using visual programming techniques. In order to tackle the speed hurdle, cloud computing infrastructures are used in order to allow the evolutionary process to be parallelized. We refer to the proposed method as Evo-Devo In The Sky (EDITS). This paper gives an overview of both the EDITS method and the implementation of a software environment supporting the EDITS method. Finally, a case-study is presented of the application of the EDITS method.*
Keywords. *Evolutionary algorithms; multi-objective optimisation; workflow system; cloud computing; parametric modelling.*

INTRODUCTION

Evolutionary design is loosely based on the neo-Darwinian model of evolution through natural selection (Frazer, 1995). A population of individuals is maintained and an iterative process applies a number of evolutionary procedures that create, transform, and delete individuals in the population.

Evo-devo-design differs from other types of evolutionary approaches with regards to the complexity of both the developmental procedure and the evaluation procedures. The developmental procedure generates design variants using the genes in the genotype (Kumar and Bentley, 1999). The evaluation procedures evaluate design variants with respect to certain performance metrics. These procedures will typically rely on existing stand-alone programs, including Visual Dataflow Modelling (VDM) systems and simulation programs (Janssen and Chen, 2011; Janssen et al., 2011). In many cases, these systems may be computationally expensive and slow to execute.

Designers interested in applying evo-devo-design methods for performance based multi-objective design exploration have typically faced two main hurdles: skill and speed (i.e. "it's too hard and too slow!"). From a skills perspective, the requirement for advanced interoperability engineering and software programming skills is often too demanding for designers. From the speed perspective, the requirement for processing large numbers of design variants can lead to excessively long execution times (often taking weeks to complete).

Previous research has demonstrated how these hurdles can be overcome using a VDM procedural modelling software called Sidefx Houdini (Janssen and Chen, 2011). Firstly, a number of simulation programs were embedded within this VDM system, thereby allowing designers to define development and evaluation procedures without requiring any programming. Secondly, the evolutionary algorithm was executed using a distributed environment, thereby allowing the computational execution to be parallelized.

Although the research demonstrated how the challenges of skill and speed could be overcome, the solution was specific to the software tools being used, in particular Sidefx Houdini. Furthermore, for most designers, the proposed approach remained problematic due to the fact that they do not have access to computing grids. This paper will propose a generalized method for evo-devo-design that overcomes these limitations. The method uses two key technologies: computational workflows and cloud computing. In order to tackle the skill hurdle, computational workflow management systems are used, called Scientific Workflow Systems (Altıntaş, 2011; Deelman et al., 2008). In order to tackle the speed hurdle, readily available cloud computing infrastructure is used. We refer to the proposed method as Evo-Devo In The Sky (EDITS).

The next section will focus on the proposed EDITS method, followed by a section describing the implementation of a prototype EDITS environment. The final section will briefly present a demonstration of how the method and environment can be applied.

EDITS METHOD

An EDITS design method is proposed that overcomes the hurdles of skill and speed in a generalized way that is not linked to specific proprietary software applications.

The EDITS method enables users to run a population-based evo-devo design exploration process. This requires four computational tasks to be generated that will automatically be executed when the evolutionary process is run: initialisation, growth, feedback, and termination. The initialisation and termination tasks are executed at the start and end of the evolutionary process respectively, and perform various 'housekeeping' procedures. In addition, the initialisation task also creates the initial population of design variants.

The growth and feedback tasks are used to process design variants in the population. The growth task will take in just a single individual with a genotype and will generate a phenotype and a set of performance scores for that individual. (In the proposed method, the processes of development and evaluation are thus defined as a single growth workflow.) The feedback task will take in a pool of fully-evaluated individuals and based on a ranking of those individuals will kill some and will select some for generating new children. With just these two tasks, a huge variety of evolutionary algorithms can easily be specified. For example, if the pool size for the feedback is equal to the population size, then a generational evolutionary algorithm will result, while if pool size is much smaller than the population size, a steady-state evolutionary algorithm will result.

The first hurdle that EDITS must address is the skills hurdle. The initialisation, feedback, and termination tasks are highly standardized and can therefore be generated automatically based on a set of user-defined parameters. The growth task on the other hand is highly problem-specific and therefore needs to be defined by the user. In order to overcome the skill hurdle, the EDITS method uses a Workflow System for defining these tasks. Workflow Systems allow users to create computational procedures using a visual dataflow programming. Users are presented with a canvas for diagramming workflows as nodes and wires, where tools are represented as a nodes, and data links as wires.

Furthermore, this approach can also be used to flexibly link together existing design tools such as CAD and simulation programs. Interoperability issues can be overcome by using data mappers, whereby the output data from one tool may be linked to the input data of another tool via a set of data transform, aggregation, and compensation procedures. This approach therefore allows parametric modelling tools to be linked to simulation tools through an external coupling, which affords the user greater flexibility in tool choice and linking options.

The second hurdle to be overcome is the speed hurdle. The evolutionary process consists of a continuous process of extracting individuals from the population, processing them with the growth and feedback tasks, and inserting the updated and new individuals back into the population. Since the tasks are independent from one another, they can easily be parallelized. Cloud computing infrastructures allow users to have access to computing grids on an on-demand basis at a low cost and can therefore be used to enable such parallelization. In the proposed EDITS method, cloud computing is used for distributing the execution of both the growth and feedback tasks.

EDITS ENVIRONMENT

In order to demonstrate the EDITS method, a prototype EDITS environment has been implemented. Three key type of software are used: a distributed execution environment called Dexen, a workflow system called VisTrails, and a set of design tools, such as CAD and simulation programs.

- Dexen is a highly generic Distributed Execution Environment for running complex computational jobs on grid computing infrastructures, previously developed by the author (Janssen et al., 2011). Dexen uses a data-driven execution model, where tasks are automatically executed whenever the right type of data becomes available. Dexen consists of three main components: the Dexen Client provides a graphical user interface for managing jobs and tasks; the Dexen Server manages the population and orchestrates the execution of jobs; and Dexen Workers execute the tasks.
- VisTrails is an open-source workflow system that allows users to visually define computational workflows (Callahan et al., 2006). VisTrails uses a dataflow execution model that is well-suited to the types of procedures that need to be defined. It also provides good support for integrating existing programs. VisTrails can be used in one of two modes: in interactive mode, VisTrails provides a graphical user interface for building workflows; in batch mode, VisTrails can be used to execute previously defined workflows without requiring any user interaction.
- A set of design tools, including CAD tools (such as Houdini or Blender) and simulation tools (such as Radiance, EnergyPlus, and Calculix). (Other popular commercial CAD tools could also be integrated with this environment. However, due to inflexible licensing policies, it is currently difficult to deploy such tools in the cloud.) The CAD tools can typically run either in interactive mode or in batch mode while the simulation programs run only in batch mode, with all interaction being restricted to text based input and output files.

The EDITS environment is delivered as a cloud based service. Cloud computing can deliver services to the user at a number of different levels, ranging from delivering computing infrastructure to delivering fully functional software (Rimal et al., 2009). These levels are typically divided into three categories: Infrastructure as a Service (IaaS), Platform as a Service (PaaS) and Software as a Service (SaaS). These levels can also build on one another.

The EDITS environment is divided into three layers, corresponding to IaaS, PaaS and SaaS, as shown in Figure 1. For the base IaaS layer, the EDITS environment uses Amazon EC2, which is a commercial web service that allows users to rent virtual machines on which they run their own software. Amazon provides a web-application where users can manage their virtual machines, including starting and stopping machines. The SaaS and PaaS layers will be described in more detail below.

The SaaS layer

The SaaS layer consists of a number of graphical tools for running EDITS jobs. Overall, there are four main steps for the user: 1) starting the server, 2) creating the growth task, 3) executing the evolutionary job, and 4) reviewing progress of the job.

Step 1 involves using the Amazon EC2 web application to start an EDITS server. This simply con-

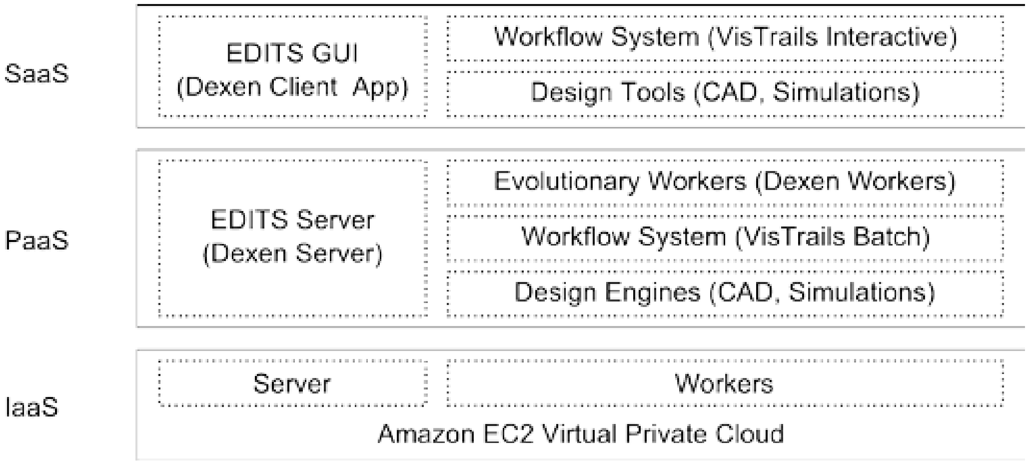


Figure 1
The three layers of the EDITS environment.

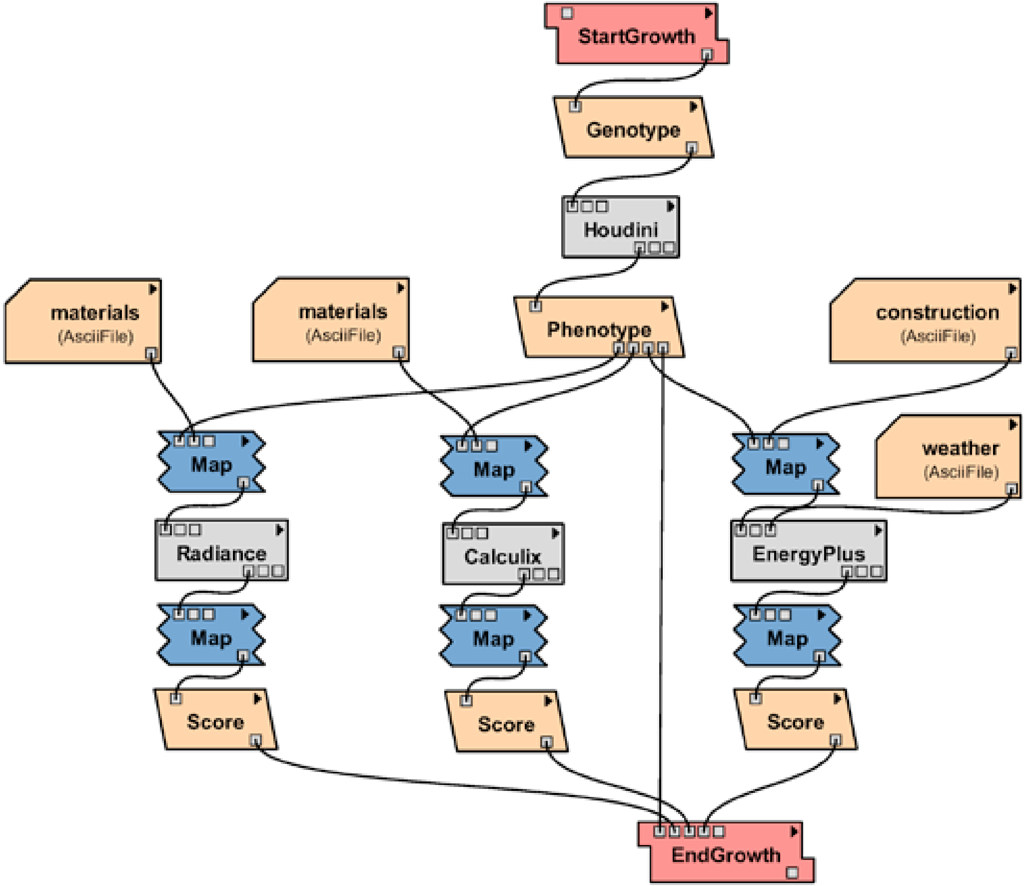
sists of logging onto the Amazon EC2 website with a standard browser, and then starting an Amazon instance. The operating system and software installed on a virtual machine is packaged as an Amazon Machine Image (AMI), and for EDITS a customized AMI has been created. This AMI is saved on the Amazon server, so it can simply be selected by the user from a list of options. The same server can be used for running multiple jobs.

In step 2, the user defines the growth task by creating a workflow with the VisTrails workflow system using a set of specially developed EDITS nodes. Figure 2 shows an example of such a workflow, consisting of a development procedure followed by three parallel evaluation procedures. The development procedure uses SideFX Houdini to generate the phenotype. The evaluation procedures use the Radiance, Calculix, and EnergyPlus simulation programs to generate performance scores. These procedures will be explained in more detail in the section describing the demonstration.

Step 3 involves executing the EDITS job. For the user, it is good if this execution could be orchestrated from within the same VisTrails environment. However, since the EDITS job may take several hours to execute, it is preferable to interact with it in an asynchronous manner. The user should be able to start the EDITS job in the cloud and then reconnect with the running EDITS job intermittently in order to download the latest results. A plugin has therefore been implemented for VisTrails that adds an EDITS menu to the menu bar for starting EDITS jobs. When a new job is started, the user can select the growth workflow, and can specify a number of parameters, including population size, mutation and crossover probabilities, selection pool size and the ranking algorithm. Once these parameters are set, a number of Python scripts required to run the job are automatically generated and uploaded to the server together with the growth workflow. The job will then start running automatically.

In step 4, the user connects to the EDITS jobs to review progress and analyse the data that is generated. Dexen has its own client application with a graphical user interface that allows users to get an overview of all the jobs that are running and to interrogate the execution of individual tasks in detail, providing information on execution time, crashes, error messages, and so forth. Data related to individual design variants can also be downloaded. However, downloading and viewing design variants one at the time can be tedious and error prone. In order to streamline this process, a set of VisTrails EDITS nodes have been created for downloading data

Figure 2
The EDITS growth workflow in the VisTrails environment.



and design variants directly from the server running in the cloud. These nodes can for example be used to create a workflow that first downloads the performance scores of all design variants and then selects a subset of these design variants for display to the user. VisTrails provides a visual spreadsheet that can be used to simultaneously display 3D models of multiple design variants (Figure 5).

The PaaS Layer

The PaaS layer builds on top of the Amazon EC2 IaaS layer, by defining an AMI for the EDITS Platform. A customised AMI was created for EDITS with all necessary software preinstalled and all settings preconfigured. The EDITS AMI includes the base operating system, together with Dexen, VisTrails, and a set of commonly used CAD and simulation programs.

The software used for orchestrating distributed execution of the EDITS job is Dexen. When the EDITS server is started on EC2, Dexen will be automatically started and all the other required software will be configured and available. The two main tasks that need to be executed are the growth and feedback tasks. Dexen maintains the population of individu-

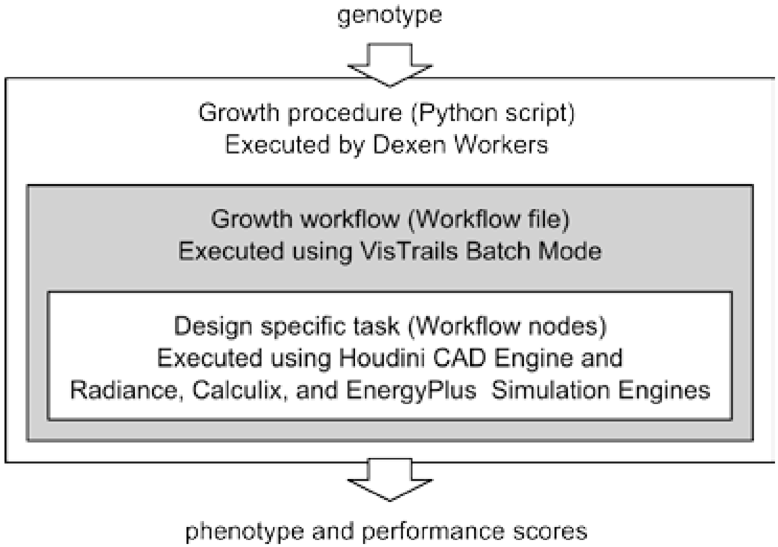


Figure 3
The software layers involved in executing the growth task. The workflow, highlighted in grey, is the only layer that needs input from the end-user.

als in a centralized database and will automatically schedule the execution of growth and feedback tasks. For the growth task, individuals are processed one at a time. For the feedback task, individuals are processed in pools of individuals, selected randomly from all fully evaluated individuals in the population. Each time either a growth or feedback task needs to be executed, Dexen will extract the individuals from the database, and send them to an available Dexen worker for processing. Once the worker has completed the task, the updated and/or new individuals will be retrieved and reinserted back into the population database.

The Python scripts for the initialisation, growth, feedback, and termination tasks are automatically generated by EDITS. The growth task is the most complex due to the various layers that are involved. The task has a nested 'Russian Doll' structure, consisting of a cascade of invocations three layers deep, as shown in Figure 3. The outer layer consists of the Python script. When this script is executed, it will invoke VisTrails Batch Mode in order to execute the workflow. Since this workflow may contain numerous nodes that link to other design tools such as CAD and simulation programs, VisTrails will then invoke these design tools. For the end-user, the complexity of the growth task is hidden, since they are only required to create VisTrails workflow.

EDITS DEMONSTRATION

As a demonstration of the EDITS approach, the design for a complex residential apartment building is evolved. The case study experiment is based on the design of the Interlace by OMA. The design consists of thirty-one apartment blocks, each six stories tall. The blocks are stacked in an interlocking brick pattern, with voids between the blocks. Each stack of blocks is rotated around a set of vertical axes, thereby creating a complex interlocking configuration.

Each block is approximately 70 meters long by 16.5 meters wide, with two vertical axes of rotation spaces 45 meters apart. The axes of rotation coincide with the location of the vertical cores of the building, thereby allowing for a single vertical core to connect blocks at different levels. The blocks are almost totally glazed, with large windows on all four facades. In addition, blocks also have a series of balconies, both projecting out from the facade and in-

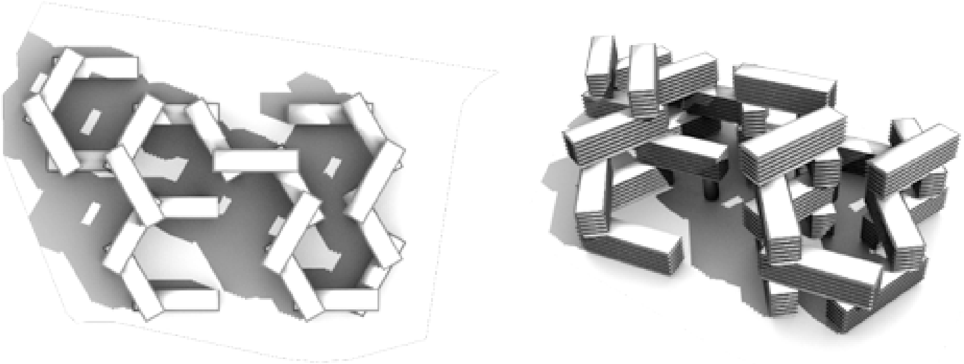


Figure 4
The initial configuration based on the original design, consisting of 31 blocks in 22 stacks of varying heights.

set into the facade. The initial configuration, shown in Figure 4, is based on the original design by OMA. The blocks are arranged into 22 stacks of varying height, and the stacks are then rotated into a hexagonal pattern constrained within the site boundaries. At the highest point, the blocks are stacked four high.

For the case study, new configurations of these 31 blocks were sought that optimise certain performance measures. For the new configurations, the size and number of blocks will remain the same, but the way that they are stacked and rotated can differ. A VisTrails growth workflow was defined that performed both development and three evaluations. The workflow shown in Figure 2 was developed for this demonstration.

Growth workflow: design development

For the procedural modelling of phenotypes, SideFX Houdini was used. For the genotype to phenotype mapping, an encoding technique was developed called *decision chain encoding* (Janssen and Kaushik, 2013). At each decision point in the modelling process, a set of rules is used to generate, filter, and select valid options for the next stage of the modelling process. The generate step uses the rules to create a set of options. The filter step discards invalid options that contravene constraints. The select step chooses one of the valid options. In order to minimise the complexity of the modelling process, options are generated in skeletal form with a minimum amount of detail. The full detailed model is then generated only at the end, once the decision chain has finished completing.

In the decision chain encoding process, the placement of each of the 31 blocks is defined as a decision point. The process places one block at the time, starting with the first block on the empty site. At each decision point, a set of rules is used to generate, filter, and select possible positions for the next block. Each genotype has 32 genes, and all are real values in the range {0,1}. In the generation step, possible positions for the next block will be created using a few simple rules. First, locations are identified, and second orientations for each location are identified. The locations are always defined relative to the existing blocks already placed, and could be either on top of or underneath those blocks. The orientations are then generated in 15° increments in a 180° sweep perpendicular to either end of the existing block. In the filtering step, constraints relating to proximity between blocks and proximity to the site boundary are applied, thereby ensuring that only the valid positions remain. In the selection step, the decision gene in the genotype chooses one of the valid block positions.

The resulting phenotypes consist of simple polygonal models. Three separate files are generated, one for each of the simulations. These models represent different sub-sets of information relating to the same design variant. These sub-sets of information are selected in order to match the data requirements of the simulation programs. In order to facilitate the data mapping, custom attributes are defined for geometric elements in the model. For example, polygons may have attributes that define key characteristics, such as *block* (e.g. block1, block2), *type* (e.g. wall, floor, ceiling), and *parent* (e.g. the parent of the shade is the window; the parent of the window is the wall). These attributes are used by the mapping nodes in order to generate appropriate input files for the simulations. The geometry together with the attributes are saved as JSON files (i.e. simple text files).

Growth workflow: design evaluations

For the multi-objective evaluation, three performance criteria were defined: maximisation of daylight, minimisation of structural strain, and minimisation of cooling load. These performance criteria have been selected in order to explore possible conflicts. For example, if the blocks are clustered close together the cooling load will decrease due to inter-block shading but the daylight levels will also reduce. If the blocks are stacked higher, then they are likely to get better daylight but they may become less structurally stable. The three performance criteria are calculated as follows:

- Maximisation of daylight: An evaluation is defined that executes Radiance in order to calculate daylight levels on all windows under a cloudy overcast sky. The amount of light entering each window is then adjusted according to the visual transmittance of the glazing system for that window. The performance criterion is defined as the maximization of the total number of windows where the light entering the window is above a certain threshold level for reasonable visual comfort.
- Minimisation of structural strain: An evaluation is defined that executes Calculix in order to calculate the global structural behaviour using Finite Element Analysis (FEA) under various loading conditions. In order to reduce the computational complexity, the building configuration is modelled in a simplified way, by grouping individual structural elements into larger wholes called *super-elements* (Guyan, 1965). The performance criterion is defined as the minimisation of the maximum strain within the structure.
- Minimisation of cooling load: An evaluation is defined that executes EnergyPlus in order to calculate the cooling load required in order to maintain interior temperatures below a certain threshold for a typical schedule. In order to reduce the computational complexity, an ideal-load air system together with a simplified zoning model is used, and the simulation is run for a periods of one week at the solstices and equinoxes. The performance criterion is defined as the minimisation of the average daily cooling load.

In Figure 2, the three workflow branches defining the evaluation procedures are shown. Each evaluation procedure includes two mapper nodes: an input mapper for generating the required input files, and an output mapper for generating the final performance score. These mapper nodes are currently implemented as Python scripts, but part of this research is the development of a graphical application for defining mapper nodes. See Janssen at al. (2013) for more details.

The input mappers transform the JSON files from the developmental procedure to the appropriate input files for the simulations. As well as the geometry information from these JSON files, the mappers also require other material information. The output mappers transform the raw simulation data into performance scores: for the Radiance data, the mapper calculates the number of windows below the daylight threshold; for Calculix, the mapper calculates the maximum strain in the structure; and, for EnergyPlus, the mapper calculates the average daily cooling load. These three evaluation scores are then provided as the final output of the growth task.

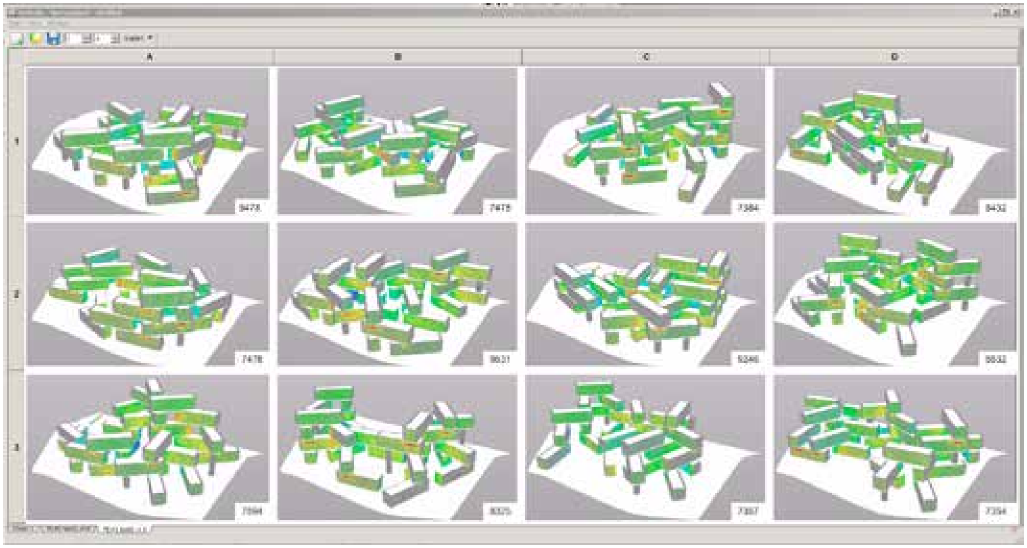


Figure 5
A set of design variants shown in the visual spreadsheet tool within VisTrails.

Results

When running the job, the population size was set to 200 and a simple asynchronous steady-state evolutionary algorithm was used. Each generation, 50 individuals were randomly selected from the population and ranked using multi-objective Pareto ranking. The two design variants with the lowest rank were killed, and the two design variants with the highest rank (rank 1) were used as parents for reproduction. Standard crossover and mutation operators for real-valued genotypes were used, with a mutation probability being set to 0.01. Reproduction between pairs of parents results in two new children, thereby ensuring that the population size remains constant.

The evolutionary algorithm was run for a total of 10,000 births, taking approximately 8 hours to execute. The final non-dominated Pareto set for the whole population contained a range of design variants with differing performance tradeoffs.

A workflow was created in order to retrieve and display designs from the Pareto front. A selection of design variants are shown in Figure 5.

CONCLUSIONS

For designers, the EDITS approach allows two key hurdles of skills and speed to be overcome. First, it overcomes the skills hurdle by allowing designer to define growth tasks as workflows using visual programming techniques. Second, it overcomes the speed hurdle by using cloud computing infrastructures to parallelize the evolutionary process. The demonstration case-study shows how the EDITS approach can be applied to a complex design scenario.

Future research will focus on the development of VisTrails data analytics nodes. This would allow users to create workflows to perform various types of analysis on the data generated by the evolutionary process, including hypervolume and clustering analysis.

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Algorithmic Design Generation

The Potential of Evolutionary Methods in Architectural Design

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Abstract. *In this paper we examine the potential of combining 2D shape packing algorithms and evolutionary methods in the design process. We investigate the ways such algorithms can be used in architectural design and how they may influence it. In the first part of this paper we introduce the theoretical framework of packing algorithms and genetic algorithms as well as the traditional design process and the nature of design problems. In the second part of the paper we introduce a software prototype that tests these algorithms in two contexts: the preliminary design of a shading façade pattern and the design of commercial housing layouts. The aim for both experiments was to generate optimal configurations based on user-defined criteria without resorting to exhaustive search. Several lessons were learned that point to the potential of evolutionary methods in architecture as well as the limitations of such methods. We conclude the paper with recommendations for further developing this research project.*
Keywords. *Evolutionary design; genetic algorithm; packing algorithm; scripting.*

INTRODUCTION

In general terms, a genetic algorithm (GA) can be characterised as a highly parallel and adaptive evolutionary search method. GAs are described as parallel searching methods because they search for solutions using the whole population of possible options as opposed to altering a single potential solution (Frazer, 1995). Since the most favourable solutions are obtained by progressive alterations within the same population over time, Frazer also refers to them as adaptive. Due to the mentioned characteristics, GAs are becoming more popular and are being researched and increasingly applied to practical problems.

Shape packing algorithms are optimization methods that attempt to pack shapes together within a set boundary. In one variation of the problem, a shape-packing algorithm is designed to pack as many shapes as possible, without overlapping them, and attempts to achieve a required minimum coverage area to minimize waste (Lodi et al., 2002). In mathematics, circle packing focuses on the geometry and combinatorial character of packing of circles of either equal or arbitrary size (Stephenson, 2005). For circles of equal size, it has been mathematically proved that a hexagonal honeycomb arrangement of circles produces the highest density (Hsiang, 1992). In architecture, shape packing can be used in many pattern-based problems where density, number of packed elements and spatial relationships between elements is important.

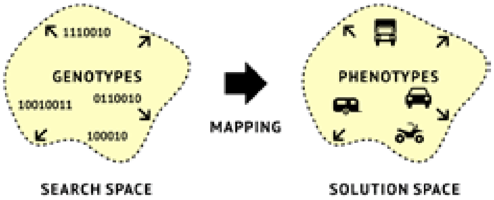


Figure 1
Mapping genotypes in the search space to phenotypes in the solution space.

The aim of this paper is to study the potential of combining 2D shape packing algorithms and genetic algorithms (GA) in the design process. It investigates the ways such algorithms can be used as tools for aiding architectural design and how these methods may influence the architectural design process itself. This will be done by conducting two experiments based on the constructive design methodology where the two 'constructs' tested would be a software prototype that combines a 2D shape-packing algorithm and a genetic algorithm tested in two experiments. This paper discusses some of the advantages as well as limitations of such tools as design aids.

BASIC STRUCTURE AND SEQUENCE OF GENETIC ALGORITHMS

Genetic algorithms consist of two separate spaces: the *search space*, containing *genotypes*, and the *solution space*, containing *phenotypes* (Bentley, 1999). The genotypes, which are the coded solutions to the problem, have to be mapped onto the actual solutions i.e. the phenotypes, which are in the solution space (Figure 1). Mapping refers to the process of assigning the genotypes from the search space to corresponding phenotypes in the solution space. This has to happen before the *fitness* of each solution can be evaluated. The fitness of a solution is assessed according to the *fitness function* that assigns scores to all solutions. The more suitable the solution to solve the problem at hand, the higher is the fitness score (Mitchell, 1995). Effectively, the solutions with higher scores will have a greater probability of being selected and reproduced in the next generation (Figure 2).

THE TRADITIONAL DESIGN APPROACH AND 'WICKED PROBLEMS'

In the second half of the 20th century researchers brought the design process to the focus of scientific study (Cross, 2007). They investigated it and outlined the basic sequence of actions involved in it, mainly in order to introduce new aiding tools and regulate it. This research has proven that systemising the design process is not an easy task mainly due to the fact that design problems are classified as 'wicked' (Rittel and Webber, 1973). This term refers specifically to the disciplines of social planning, politics and design. Firstly, in most of the cases the design problems cannot be comprehensively formulated. This is due to the fact that nowadays the design process of a specific building involves collaboration between different parties, which hinders arriving at specific requirements early in the project development. Usually, the design problems appear and become clearer as the process proceeds. Secondly, since design is a collaborative effort between different parties, it has to unite what are sometimes radically contradictory interests. It has to take into account a number

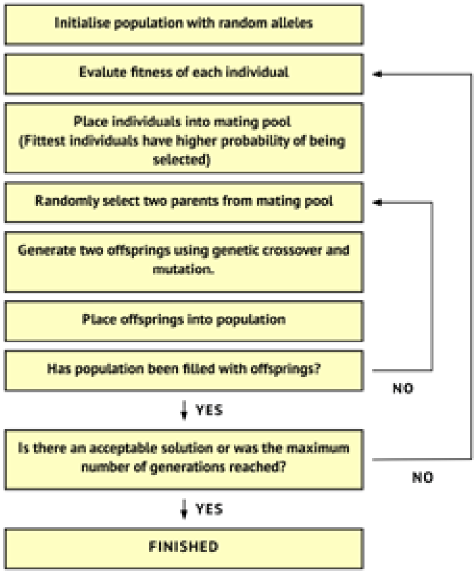


Figure 2
Basic genetic algorithm sequence.

of other factors such as moral and social aspects, aesthetic impact and sustainability. Thus, the design solutions cannot be rationalised since design is not merely a pragmatic problem-solving or simple optimisation leading to one right solution. Even though usually one solution is sought, the possibilities for arriving at it are limitless. Thirdly, because there is no linear sequence for a design process (Lawson, 2005), there is also no apparent beginning or end to it. The information needed to make decisions is never fully complete and thus the state of the design problem is constantly evolving. Furthermore, in modern design thinking, problems and solutions are deemed to emerge together during the design process. That is, finding design solutions may cause other, "higher-level" problems somewhere else. Therefore the design process involves finding a balance between solving some problems in one place and causing undesirable effects somewhere else. Rittel and Webber emphasize that these 'wicked' design issues, unlike science, depend heavily on the designer's subjective value judgements. These main characteristics are obstacles when working with algorithms and computer programs that need specific requirements and clearly defined rules in order to perform their tasks.

THE CONSTRUCTIVE METHODOLOGY

This part of the paper will describe two algorithmic experiments employing custom software created by the authors using the MAXSCRIPT scripting language for Autodesk 3ds Max. The software integrates a genetic algorithm with a shape-packing algorithm that operates on any 2D boundary. The first experiment explains the basic logic and functioning of the GA based on façade pattern design. This supplied valuable data for the discussion of the advantages and limitations of this tool. The second experiment concerns a more realistic case of housing layout design based on a real-life master plan. It has to be pointed out here that both of the cases present an integrated approach towards evolutionary design put into practice. The experiments will focus on first designing a pattern or layout and then optimising it based on the design criteria set by the designer.

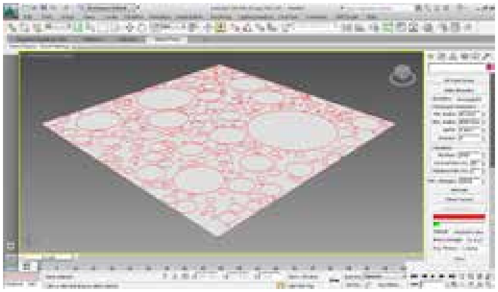


Figure 3
The user interface of the custom-developed genetic software in Autodesk 3ds Max.

EXPERIMENT 1: FAÇADE PATTERN DESIGN

The design of the first experiment involves the creation of a panel façade of size 10,000x10,000 mm. The main design goal is to achieve 40-50% of the area coverage of the designed pattern in order to provide the required shading. The second design aim is to design the pattern with 2000 circles of various radii. Both of the design goals have to be achieved following basic criteria set up at the beginning of the process using the custom-designed software (Figure 3). These are as follows:

- Min. Radius: 50 mm
- Max. Radius: 8000 mm
- Buffer: 20 mm

The range for the minimum and maximum radii was decided bearing in mind that the wider the range the more variety will be sustained in the population. These two values could also represent the radii of the smallest and biggest drills used for making the pattern. The reasons for choosing the radii range can be very different. The 'buffer' parameter refers to the area between circles where no other elements are allowed.

Genotype and phenotype

Since the design aims at creating a façade pattern made out of circles of various sizes the radius is the only information contained in the genotype (Figure 4). As shown, the genotype is the number falling within the specified range, where the phenotype

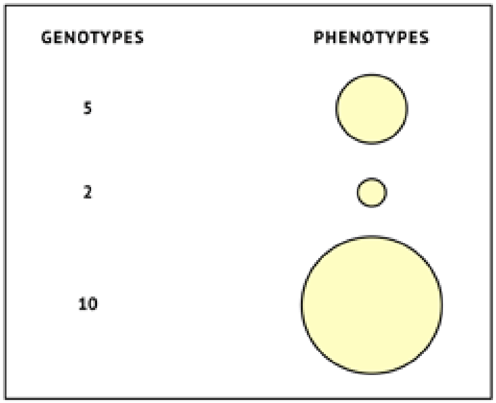


Figure 4
Exemplary genotypes (radii) and phenotypes (circles).

is the assigned representation of the genotype – in this case it is a circle of that particular radius.

Fitness function

In order to encourage variety within the panel the fitness function favours the circles with radii as close to the minimum or maximum radius values as possible. This will secure more diversity within the population and will create more interesting patterns. Thus, the fitness function is defined as follows:

$$F = \frac{|R_i - R_{av}|}{R_{av}} \quad (1)$$

where *F* is the fitness of the individual, *Ri* is the radius of the individual circle, and *Rav* is the average of the specified minimum and maximum radii.

The GA sequence

The initial population is created randomly, covering the entire range of possible solutions (search space). In case of the script used for this experiment the new individuals were created using a circle-packing algorithm until the maximum number of attempts for fitting more individuals has been reached (in this experiment it was set at 50,000 attempts). In such a case usually the initial population does not reach the maximum number of individuals (in this case 2000 individuals). After the initial population has been generated the fitness of each individual is calculated. The obtained fitness scores are then used for selecting the fittest individuals and placing them in the mating pool. We specified a constant 50% survival rate and a 1% mutation rate throughout the experiment and implemented a "roulette wheel" selection method to select the fittest candidates while maintaining a similar diversity to the one found in natural selection. After the individuals for the mating pool have been selected the process of reproduction begins using crossover and mutation of their genotypes. The process of generating populations continues until a termination condition is met. Termination takes place either when the population target is met or when the algorithm reaches the maximum number of attempts to fit the individuals (50,000). The section below describes the results of the four tests created based on the rules described above.

Results

We conducted four tests in order to meet the design requirements and solve the stated design problem: Achieving area coverage of 40-50% with 2000 circles. In each test, we iterated through four generations (Table 1).

Discussion and Comments

As the results show, meeting both of the design goals where the fitness function is awarding the radii from the extremes of the range of 5-800 cm, is rather unlikely to be achieved in the span of 4 generations even if the number of attempts is 50,000. The outcomes might have been different if the number of attempts was increased to 100,000 or more. This is, however, an area for further research that lies outside of the scope of this experiment.

Compared to the non-optimised first generation of packed circles, it is evident from conducting only four tests, that applying the GA dramatically increases the number of circles to meet the goal to pack 2000 individuals within the prescribed boundary (Figure 5), but that has two side-effects: 1) The average radius of circles decreases, and 2) the over-

Table 1
Results of running four tests each with four generations.

Test No.	Generation No.	Packed individuals	Area Coverage (%)	Avg. Fitness	Avg. Radius (mm)
1	1	195	60.26	0.98	193.42
1	**2**	**1489**	**44.28**	**0.98**	**86.55**
1	3	2000	34.73	0.98	70.47
1	4	2000	27.82	0.98	64.84
2	1	212	55.78	0.95	190.03
2	**2**	**1401**	**45.42**	**0.98**	**90.24**
2	3	2000	34.62	0.98	70.15
2	4	2000	26.72	0.98	63.20
3	1	217	50.66	0.95	186.06
3	**2**	**1449**	**49.36**	**0.98**	**83.92**
3	3	2000	31.34	0.98	66.57
3	4	2000	25.09	0.98	61.68
4	1	204	57.93	0.95	192.08
4	**2**	**1479**	**45.90**	**0.98**	**86.58**
4	3	2000	34.20	0.98	69.44
4	4	2000	27.52	0.98	64.19

all coverage area of these circles decreases as well (Figure 6). Also, it can be concluded that the bigger the coverage area, the smaller the number of elements. In all of the tests the maximum number of circles was achieved when the coverage area was consistently below 40%. Based on that, the main design goals had to be revised. Because the GA proved that both design goals couldn't be achieved simultaneously, the designer has to decide which is a priority – the coverage area or the number of packed elements. Since the main aim of the experiment was based on creating the required shading pattern, the coverage area took precedence. Therefore the façade pattern with the coverage area within the range and achieved with the biggest number of circles was chosen as the proposed design solution. In the four conducted tests, this was achieved in the second generation of the third test with 1449 packed individuals and 49.36% coverage area (Figure 7).

It is clearly visible from both the data and the visual graphs (Figure 6) that even after the maximum number of packed elements has been achieved the GA was still breeding a population of increasingly smaller circles. This occurred due to the fact that the fitness function was awarding both extremes – the smallest and the biggest circles. The mating pool quickly biased itself towards smaller circles after the first generation because at the point when the maximum number of elements was reached there were far more circles with radii closer to the minimum than those closer to the maximum radius. That is, since there were a larger number of smaller circles and because they were considered just as fit for breeding as large circles, there was a higher probability of choosing them for breeding the next population. This *strength in numbers* phenomenon initiated a vicious cycle of breeding smaller and smaller circles while larger circles quickly became extinct. The solution seems to approach a plateau after the third generation. An interesting contradiction is that the overall results did not improve with the subsequent generations even though the individuals' fitness was increasing. From an interesting perspective, this result supports a case for diversity where even if individual fitness is high, the overall performance of the population is unsatisfactory due to a lack of diversity.

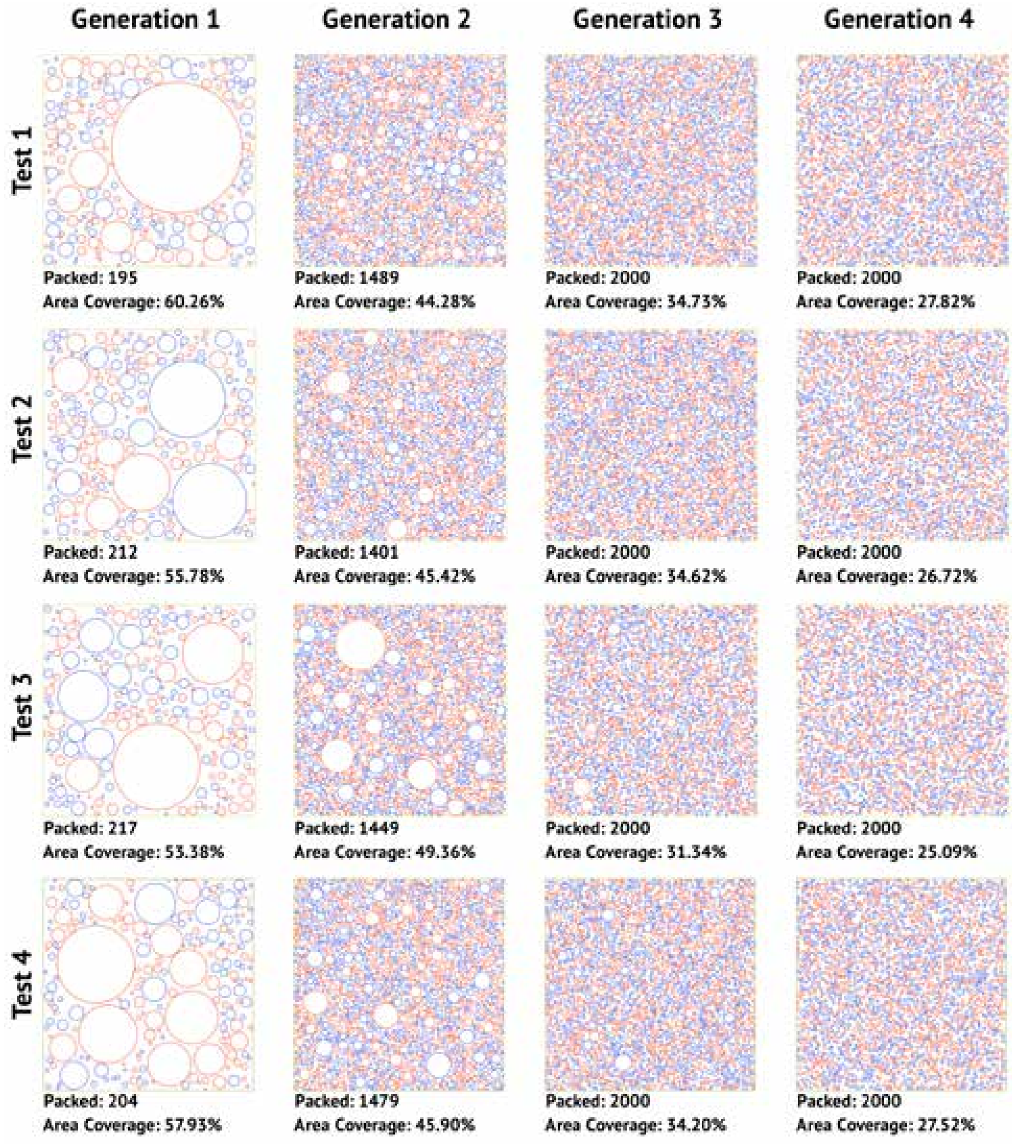


Figure 5
A visual representation of the test results. The blue circles represent the parents chosen for breeding the next generation.

Figure 6
Left: Graph representing the decreasing average radius over four generations in all four tests.
Right: Graph representing the decreasing coverage area over four generations in all four tests.

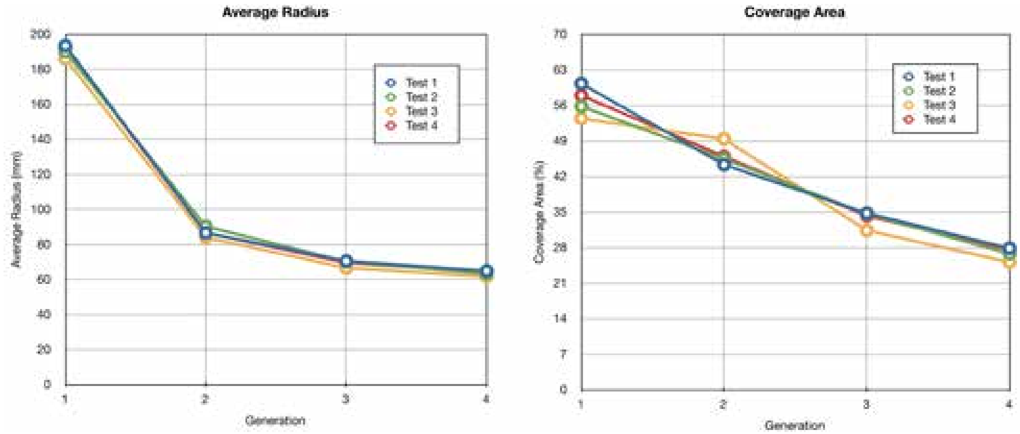
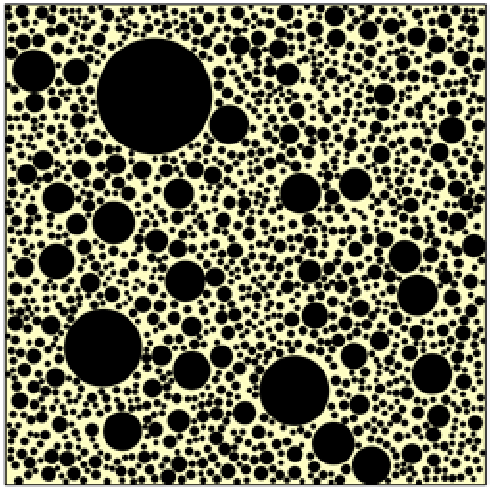


Figure 7
The proposed façade pattern based on overall results.



EXPERIMENT 2: HOUSING LAYOUT DESIGN

The second experiment explores the application of a genetic algorithm to the design of a housing layout. As an early stage test, it ignores the vast number of variable factors that influence the design of such schemes and focuses on achieving the greatest density of housing units. This 'House Packing' script enables the user to define a series of areas (representing buildable plots of land), the program then places houses around the perimeter of these areas and orients them to the nearest edge (representing a road). The fitness of each individual is calculated based upon their proximity to their nearest neighbour. This factor of 'remoteness' ensures that the density of houses in subsequent generations increases.

The program was tested on a case study housing development that has recently been granted planning permission. For the purpose of this research, this provided a realistic framework onto which the program could be applied. The program is able to vary the size of the houses within what has been defined as a realistic range, based upon the house sizes found in the case study. The intention is to achieve a more realistic configuration of houses. The input parameters were as follows:

Phenotype Parameters:

- Min. Radius: The minimum separation distance between houses.
- Min./Max. Length: The range of lengths of the houses being generated.
- Min./Max. Width: The range of widths of the houses being generated.
- Dist. To Road: The minimum distance from the road at which houses can be placed.

Population Parameters:

- Maximum: Sets the maximum number of houses to be generated.

- Survival Rate (%): Controls the percentage of the population that will survive and be allowed to breed the next generation.
- Mutation Rate (%): Controls the chances of an individual within the population to mutate.
- Max. Attempts: The maximum number of attempts that the computer is given to place the houses correctly.

Results

The two variables that control the effectiveness of the genetic algorithm are the survival rate and the mutation rate. To find optimal values for these, we carried out a series of evaluations that first tested the system at varying survival rates and then varying mutation rates. We tested the program over five generations on the case study layout. For each setting, we recorded the three read-outs: 'Packed', 'Coverage Area' and 'Average Fitness'. This gave an indication of how well each rate was performing, though the most telling result was the average fitness score as this is more directly linked to the overall efficacy of the algorithm. It would seem that the rate showing the greatest increase in average fitness over consecutive generations should be selected as the optimal setting. Over five generations this would appear to be the 100% survival rate. However, a survival rate of this magnitude stifles the genetic algorithm by preventing it from removing poor performing individuals. As a result the values for 'Packed', and 'Coverage Area' tend to peak very early, and more often than not exceed those achieved by lower survival rates, as the program attempts to squeeze more and more houses onto the site. The average fitness score on the other hand will usually remain relatively low, since the proposed solution still contains a number of poor performing individuals. The results recorded in this experiment appear contradictory, as the highest average fitness score is achieved by the 100% survival rate. The problem with such a high survival rate is that the algorithm is relying entirely on the mutation of individuals to increase the average fitness. It is more of a brute force trial and error approach rather than systematically breeding a better solution. This method appears to work for this particular experiment, as the fitness score is very closely linked to the number of individuals placed (more individuals = lower factor of remoteness = higher fitness score). However the purpose of this experiment is to test the potential of the genetic algorithm, and thereby following a method that nullifies part of the breeding process would be contrary to that goal.

We found that the optimal survival rate was 60% and mutation rate was 40%, this coincides with experiments by other researchers that suggest a mutation rate of approximately 50% (Elezkurtaj and Franck, 1999). Using these settings, we ran the algorithm for 15 generations to discover the effectiveness of the optimisation process. The results show a general positive trend in the average fitness score and number of packed houses, indicating that the optimisation process is functioning correctly (Figure 8). What is interesting is the amount of fluctuation between generations. These results indicate a pattern of 3-4 successive increases followed by a significant decrease, the magnitude of which reduces with each repetition. This is an indicator of how the genetic algorithm works. Over successive generations,

Figure 8
Left: Generation 1. Number Packed: 364, Area Coverage: 25.61%, Average Fitness: 2.56. Middle: Generation 7. Number Packed: 373, Area Coverage: 24.98%, Average Fitness: 2.58. Right: Generation 15. Number Packed: 380, Area Coverage: 24.61%, Average Fitness: 2.63.

the range of fitness scores will decrease as they all become fitter (and the average fitness increases). The result of which, in terms of the roulette wheel selection method, is that each individual has a much more equal chance of being in the percentage of the population which survives to the next generation (the survival rate). Conversely, they also have a more equal chance of being removed from the population. This is demonstrated in the results where after 3 generations at a 60% survival rate, new individuals with lower fitness scores replace 40% of the relatively high scoring population.

Discussion and Comments

It is clear that a genetic algorithm based design aid holds great potential in increasing the efficiency of the commercial housing design process. The ability of this kind of software to act as a catalyst for design ideas whilst simultaneously conforming to a plethora of constraints is something that, as the need for greater efficiency and precision within the design process grows, is going to prove invaluable. The most pressing question raised by this research is the way in which the software should be integrated into the design process.

For this experiment we shared the results with a group of architectural practitioners to gauge their reaction. Unsurprisingly, this expert consultation exposed a desire amongst the designers to have a greater amount of input in the generation of a solution. This gave an interesting insight into the way that they feel about the software. One expert questioned the ability of software to replicate the "human ability to … make a subjective judgement", demonstrating a lack of trust in the system to generate a complete design solution. The designers want the software to carry out the time consuming, menial tasks, enabling them to focus their time on the more skilled areas of design, but do not wish the software to shift all decision making from human to machine. The lack of trust also answers the question of the potential marginalisation of the architect's role through the advancement of digital design tools. The designers do not see the technology as marginalising their role; they feel that "If anything the development of IT in design has given more control back to the designers". This further reinforces the role of the program as a design aid, not as a complete design solution.

CONCLUDING REMARKS

The two experiments we have conducted reinforce the notion that evolutionary methods have many advantages. Most importantly, the experiments illustrated that evolutionary methods are indispensable when dealing with a large potential solution space. Rather than conducting a manual and exhaustive search for the best solution from a large data set, evolutionary methods allow the designer to set target goals and input parameters and rules that act together to search the population for the best possible candidates and use that pool of candidates as an input to breed an even better solution. Genetic algorithms allow designers a more precise method to achieve the desired goal as it faithfully applies the states rules and precisely measures the performance of individuals and the overall population with each generation. Given their parallel search nature, genetic algorithms can help us speed the whole design process when the pool of options is large. Additionally, evolutionary methods are capable of supplying very surprising outcomes aiding the designer's creativity and suggesting new solutions. Finally, due to their high efficiency, evolutionary methods allow the design more time to focus on the quality of the design, omitting menial tasks such as ensuring that the proposed design is compliant with the stated goals and constraints.

The experiments also exposed some important limitations of these methods. Due to the 'wicked' nature of design problems, it is not always feasible to state and code clear design rules and objectives. The design process is highly dynamic and often changes course. Although possible in future iterations of the software, the genetic algorithm code we have developed was not designed to handle changing design goals between generations. The addition of new parameters and fitness score methods between generations could prove even more difficult to implement. As most computer-based systems, genetic algorithms cannot replace the tacit knowledge, common sense, and intuition of human designers. In particular, these methods cannot replace human judgment since it is difficult to encode in the algorithm, as it is not based on clearly definable rules. Yet, we believe these methods fundamentally change the design process and the role of the designer. We envisage the designer mutating from the role of the supreme creator of the final outcome to the role of the maker of rules. In partnership with sophisticated evolutionary systems, the designer can then explore the plethora of solutions offered by these methods fluidly shifting its rules and input parameters that in turn alter its path of evolution.

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Genetic Algorithms Applied to Urban Growth Optimization

Solar envelope and solar fan

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Abstract. *This work is a research on the application of genetic algorithms (GA) to urban growth taking into account the optimization of solar envelope and sunlight in open spaces. It was considered a typical block of a Spanish grid, which is the most common subdivision of the urban land in towns situated in Argentina. Two models are compared, one in which the growth has no more limitations than building codes. The other one, in which the growth incorporates the solar radiation as a desirable parameter.*
This way of parameterizing configures a bottom-up method of urban growth. No top-down decisions intervenes in the growth process.
This tool proves to be useful at early stages of urban planning when decisions—which will influence along the development of the city for a long time—are taken.
Keywords. *Genetic algorithms; solar envelope.*

INTRODUCTION

This work analyses the application of genetic algorithms (GAs) (Mitchell, 1998) to parametric urban design, considering access to solar radiation. Parameterization allows the continuous control of the design process and evolutionary algorithms (Russel, 2010) optimize the solar access. We develop a simulation of urban growth according to current restrictions and building codes (Leach, 2004).

Spanish towns in Argentina share a same urban pattern: a 45º-rotated grid (Randle, 1977). This grid is suitable for a plain land with no mayor geographic accidents like our grassy prairies. A main square, which derives from the Spanish "plaza", determines the centre of the grid and the main public buildings are situated around: the church, the government offices, the school, and the police station. Housing is distributed in the blocks around the town core.

Our case study , Lincoln, is a town situated in Argentine Pampa. Towns founded after Independence period (1816) like Lincoln (1865) (Tauber, 2000), followed the Spanish pattern. This town, bases its economy on soya crops and the cash flows that this activity produces every year are reflected in the economic growth (Forrester, 1970).

With this data, the author built an urban model which reaches maximum growth. The study is applied to two blocks in the town centre area (Figure 1). There is a wide range of uses situated in this area: commercial, housing and office buildings. The highest density is concentrated in this zone. The intention is to show how an urban block can grow different if environmental criteria are applied.

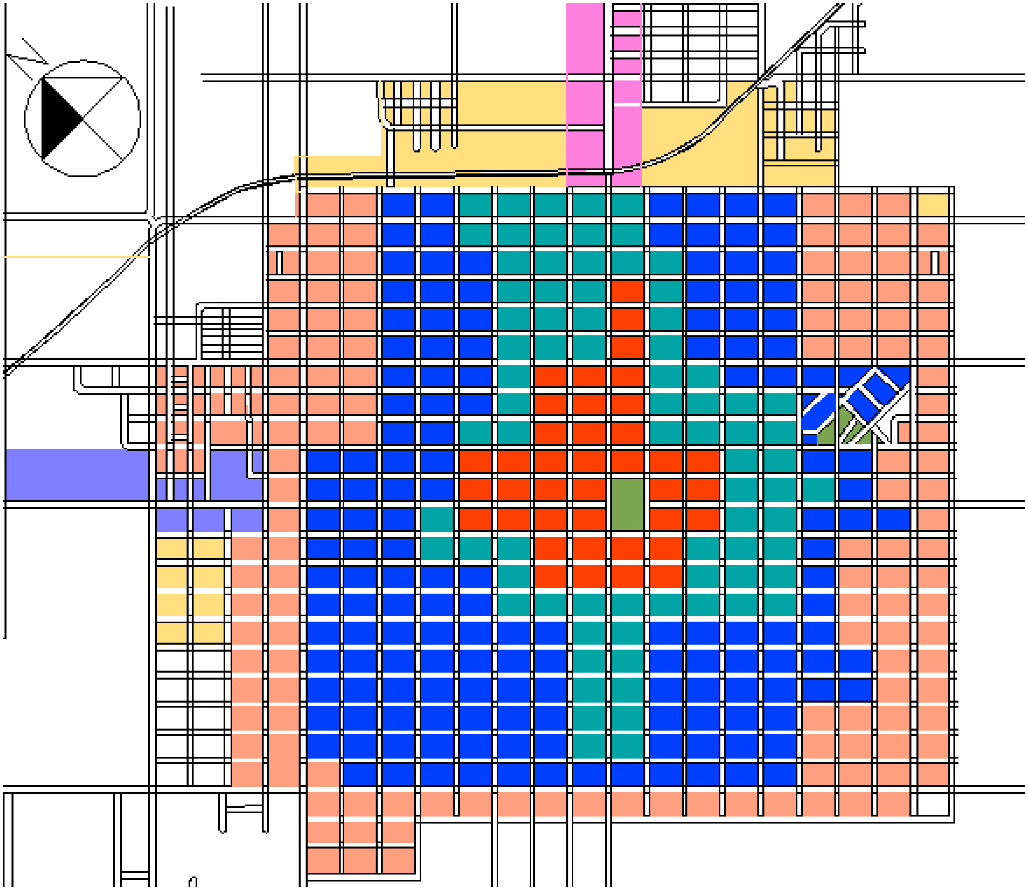


Figure 1
Lincoln zoning: high density in centre town area: offices, housing, trade, lower densities concentrically situated: housing, trade, ,small industries, outside: rural areas.

These towns have experienced a fast growth during last years as soya prices began to rise. Urban development has occurred without any planning except for the current law that regulates the use of land, which was promulgated in the ´70s. This is the Decree- Law 8912/77 [1] and it does not reflect environmental issues, as the solar envelope concept [2].

In this work, solar envelope allows urban dwellings to satisfy a two-hour period of solar radiation (11AM to 1PM) all year round (Niemasz, J et als, 2011). Solar fan [3] is another tool which defines a volume of a four-hour period (10 AM to 2 PM) of solar radiation in open spaces in the block core. It considers the growing season until the average first frost date which is 1st April in the Southern Hemisphere. The intersection between these two shapes defines a buildable volume.

Another simulation with no solar restrictions is developed. The comparison between the two models permits the urban designer to take into account solar access from the very beginnings of the codification process and to reflect this issue in the building code, making the necessary corrections to the current one.

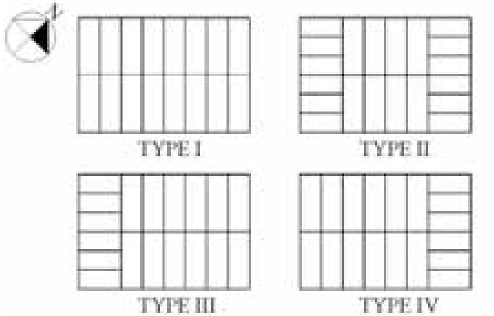


Figure 2
Types of blocks in Lincoln urban grid.

THE CURRENT BUILDING CODE

The urban land is private except for public buildings. The owner must follow the restrictions and recommendations of the Building Code which refers to the plots as the units that configure the urban block.

The law referred to the use of land lets the building occupy at maximum 60% of the plot surface. A 40% must be free for correct ventilation and daylight. This coefficient is called Land Occupation Factor (LOF). No lateral free space less than 4m wide can be left as it is considered that the building can only receive daylight and ventilation from the front urban space, backyards or lateral urban spaces. Windows must ventilate and receive light from those spaces exclusively. Dividing walls between different plots must not have openings for ventilation and daylight. Therefore, they are blind.

Backyard dimensions are determined by an imaginary line that crosses the plot 25m far front borderline, which constitutes the building limit and configures the block core together with the other plot backyards. This restriction makes the buildings tend to occupy the plot from one side borderline to the other one.

All these regulations make the individual buildings to configure a solid volume like a ring with an open space in the centre of the block called the block core.

The maximum built surface allowed can be from 1.2 times the plot´s surface up to 2.75 times, in our case study. This coefficient is called Total Building Factor (TBF). It depends on the urban zone where the plot is placed. In our case, as the block is in the centre town, TBF is 2.75. In order to simplify the process, each buildable volume is divided in modules which occupy 0.6 plot surface and rise up to complete the maximum allowed. Maximum height is 24m or approximately eight-storey high.

TBF can be increased if the floor plan surface is smaller than the allowed by LOF. This coefficient also increases if the building is receding, leaving an open space in the front. These regulations promote to build higher receding buildings that shade into the lower neighbour ones and their backyards. It can also allow appearing isolated buildings separated 4m from each borderline, in which case, environmental conditions in open spaces tend to worsen.

THE URBAN MODEL

Lincoln is divided into a rectangular grid oriented NE-SW. Unlike other Pampa towns, the grid is not square; but it is rotated 45° NE as most Spanish urban grids in Argentina. This rectangular shape provokes that NE façades have best orientation as we are in the Southern Hemisphere but the remaining ones have not good orientation, especially the SW and SE ones (Figure 2). Different kinds of blocks were analyzed from the town plan.

Blocks are 121m length and 81m width. Type I has sixteen plots of 618m2 each. Half the block looks NE and the other half looks SW. In the case of middle plots, a space in the backyard is left free to configure what is called the block-core. This open space ensures daylight and ventilation to the rear façades. The buildings situated in the corner plots are not compelled to leave this open space as they have two façades looking to streets where to ventilate and get daylight.

Type II has twelve plots of 412 m2 and eight plots of 618 m2. Four blocks look NE, another four look SW, six look SE and six look SW. Type III has twelve plots of 618 m2, six looking NE and six, looking SW. It has also six plots of 412 m2, looking NW. Type IV is a mirrored image respect to Type III.

Street width is 18m for NO and SE streets and 23m, for NE and SW streets. The relation between

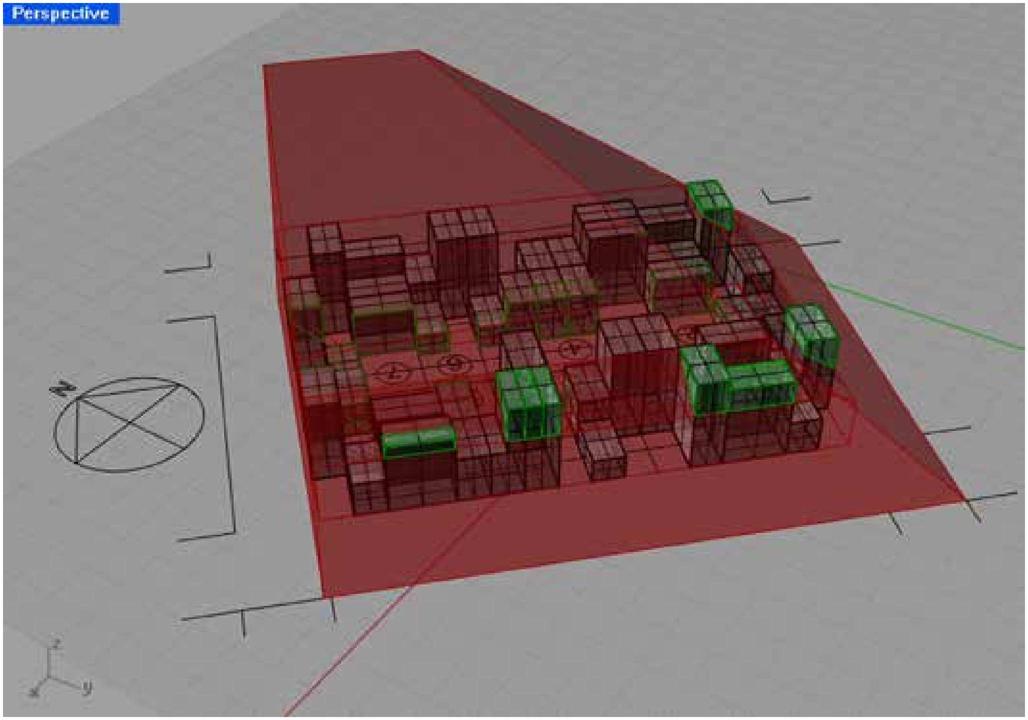


Figure 3
Solar envelope for 20th June 11AM to 1PM showing the buildings according to current building Code.

street width and building height is 3:2 for SE streets (18m) and 5:7.5 for SW streets (23m) for this specific urban grid (121m x 81m).

METHODOLOGY

The objective of this work is to compare the two models: the built block according to the current Code and another one with solar restrictions and maximum growth for a Type I and a Type II blocks.

The whole drawing is parameterized in Rhinoceros © [4] by means of Grashopper [5]. In the first case, an urban block is modeled following the current building Code (Figure 3).

Each plot reaches its maximum buildable volume according to height limit (24m), LOF (0.6 plot´s surface) and TBF (2.75 plot´s surface). No more limitations are taken into account. A wide variety of buildings which exceed the bounding box appeared.

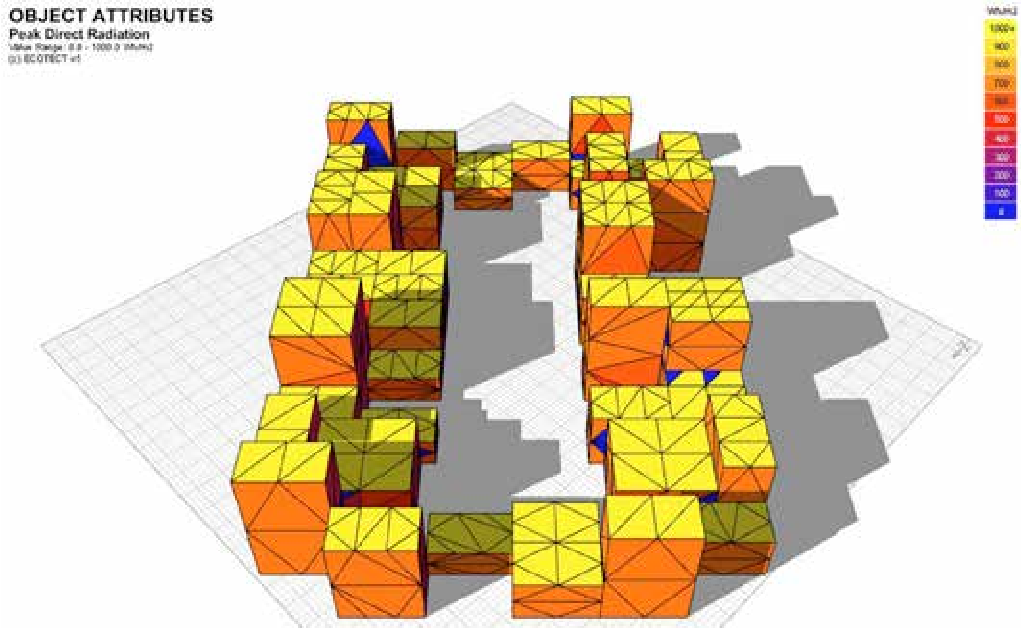
After that, we proceed to apply solar restrictions. These solar tools determine a solar buildable volume. It is designed for a two-hour period from 11 AM to 1PM.

The first tool solar envelope is applied to the model. As it can be seen in Figure 3, the Code does not make any difference between different orientations in order to regulate maximum height.

As we observe the shades projected onto the adjacent streets —especially SE and SW— we can easily infer that they reach the façades of the block in front of ours (Figure 4). This image has been exported to Ecotect© by means of GECO [6], which is a Grasshopper plug-in. This image clearly shows shades and levels of direct radiation of buildings at noon for June, 20th.

The other tool, the solar fan, is the void that has to be left in order to assure a four-hour period of so-

Figure 4
Shades for 20th June (winter solstice) at noon in the non-optimized model.



lar radiation in open inner spaces of the urban block during growing season. This open space is called 'block core' in the Building Code and it is composed by all the backyards of the plots. Only corner plots are exempt from integrating this space. As it is observed in Figure 5, some volumes exceed the core block when only considering current regulations.

After this, a model considering solar envelope and solar fan was obtained by means of GAs. These algorithms are used in optimization processes (Goldberg, 1997). In this case, one called Galapagos has been run to maximize built volumes in each plot. The buildable shape is obtained by the Boolean intersection between the solar envelope and fan. Then, the algorithm develops the maximum allowed quantity of modules and their arrangements, considering building regulations inside this bounding shape. The Boolean difference between the buildings and this bounding box is minimized, reaching in nearly every case, a value of zero. The results are shown in Figure 6.

In Figure 7, the projected shade of the optimized volume is analyzed in Ecotect. Shade on the SW and SE streets does not reach the façades of the blocks in front as they are limited by the solar envelope. The core block receives enough solar radiation during a four-hour period during growing season.

Type II block was also analyzed in the same conditions as Type I and the results are shown in Figure 8. As the core block varies its dimensions, buildings on NW and SE sides are not so restricted in their rear facades.

RESULTS

After modeling the normal Type I and II blocks and the optimized ones, we proceed to compare the results between the experiences shown above.

In Type I, while in the normal model, the maximum height is 24m or eight-storey in the whole block, in the optimized one, it has to be reduced to 15m or five-storey on SW façades to avoid shading over the neighbour block. In SE façades, this is-

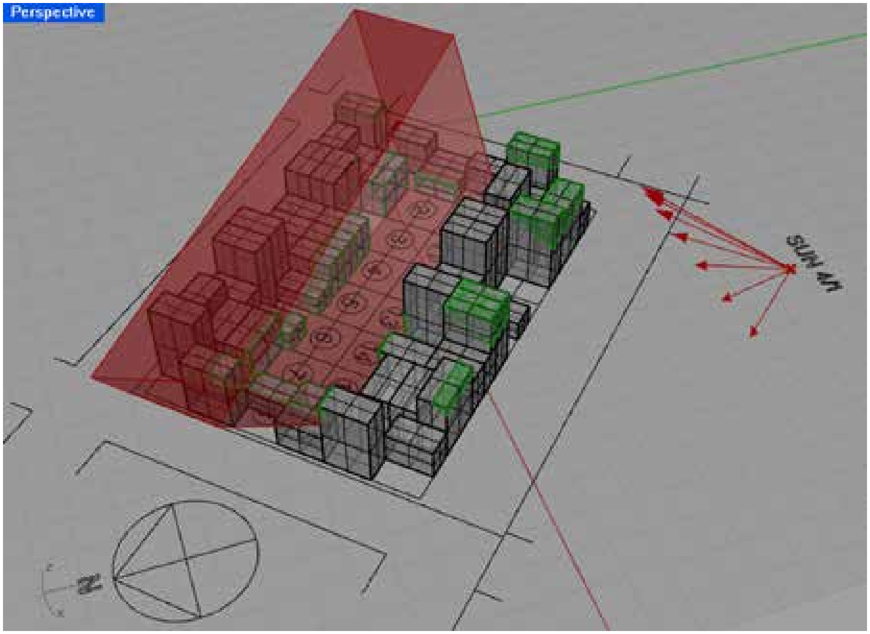


Figure 5
Solar fan showing volumes that exceed the block core (green areas) for non-optimized model.

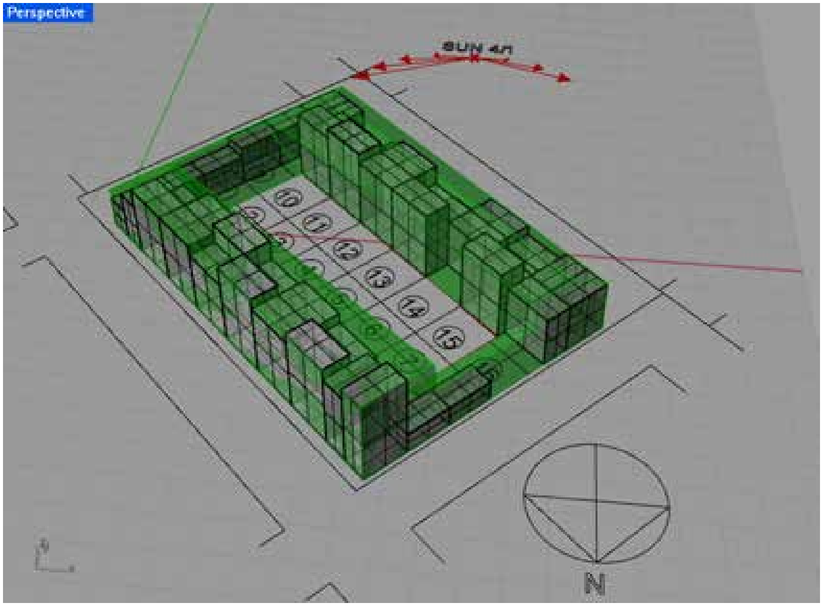


Figure 6
Optimized built volume inside the solar bounding box.

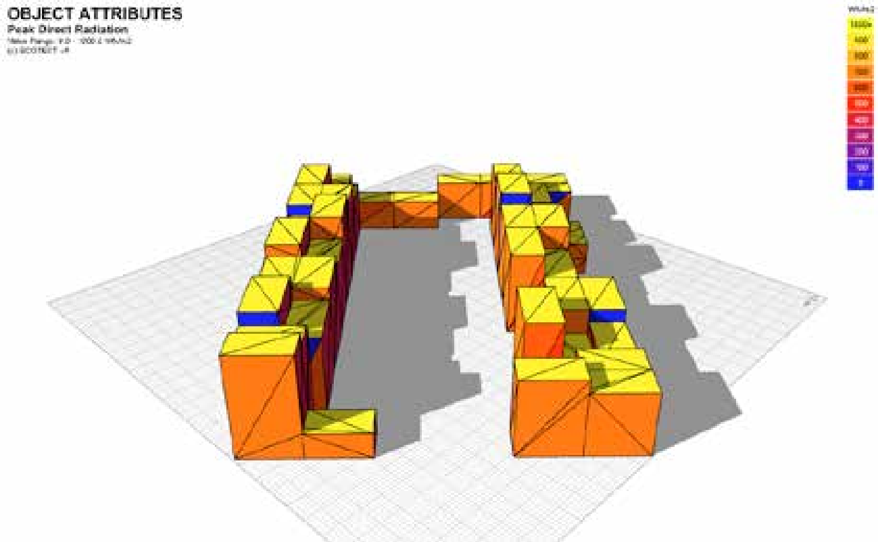


Figure 7
Optimized model in Ecotect showing the projected shadows for 20th June, at noon}.

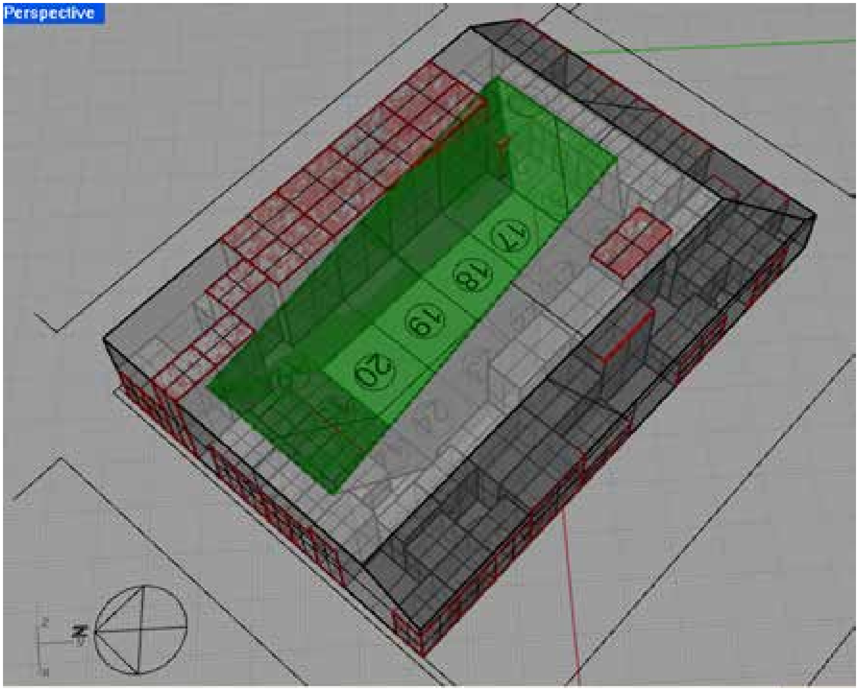


Figure 8
Type II block Boolean difference between solar envelope and fan with optimized built volumes.

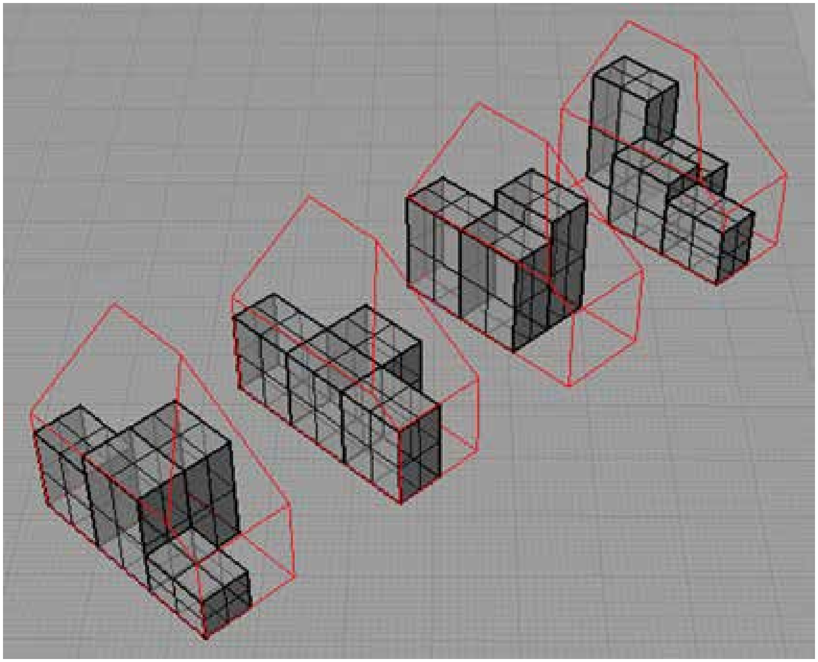


Figure 9
Alternative buildings obtained with GA for SE plot in block Type II showing bounding box in lines.

sue is even worse; the height is lowered to 12m to maintain the built volume inside the bounding box. These buildings can be terraced up to eight-storey height only on the rear part.

When analyzing Type II block, the portion of the buildings that exceeds the bounding box is shown in red. It sums approximately 79 m2 (Figure 8). Even when, in the plot 17, the GA improved the module arrangement, this plot cannot be completely built up to 2.75 TBF. Maximum height should be reduced to seven-storey (21m) in plot 18 and six-storey in plot 17 in the rear façades of the buildings.

The GA produced several alternatives that are comprehended into the solar bounding box. Some of these possible arrangements for SE plot are shown in detail in Figure 9. The same procedure was followed with each plot.

NE corner blocks are the only ones which can reach maximum height in their whole surface. The other ones have to be terraced.

Two different types of blocks, I and II, are shown in Figure 10. Both types differ in the dimensions of the block cores as the plots have different number of plots and arrangements (Figure 2). As the core block increases in NW-SE direction, the buildings on these façades have to diminish their height.

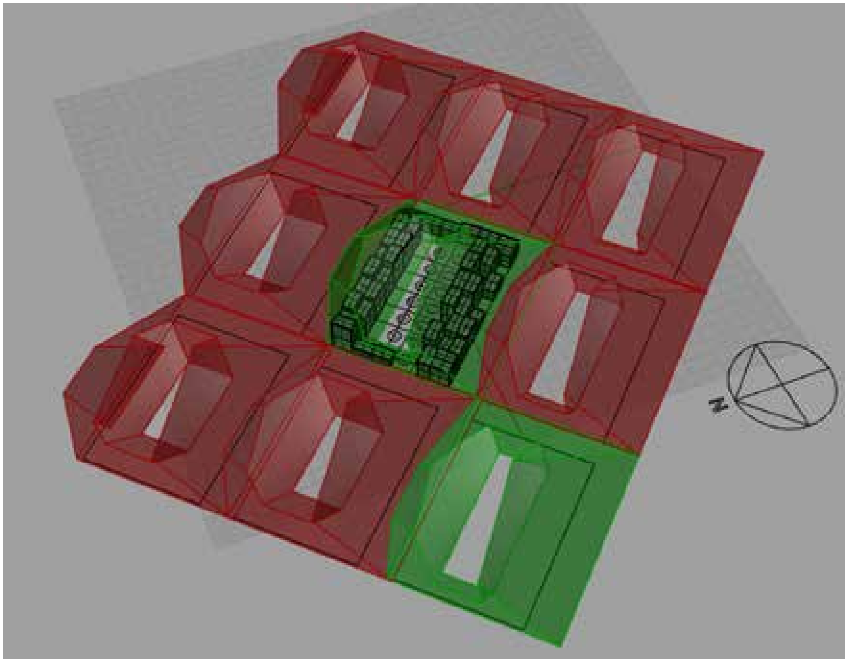
DISCUSSION

The use of these tools applied to urban design permits the improvement of environmental conditions in buildings and open spaces. It can be applied to determine urban grid characteristics like:

- block dimensions
- street widths
- maximum heights differentiated by orientation
- core block dimensions

The solar envelope and fan as prescriptive tools in urban design have to be studied together with energy savings, developable density and infrastructure costs as well as local climate conditions. Our

Figure 10
Urban tissue with different types of blocks: Boolean difference between solar envelope and fan.



typical urban grid promotes adjacent buildings which reduce heat losses through dividing walls. This is the reason why this work considers the block as an individual at urban level and as a whole at plot level. In this bottom-up process [7], the individuals can perform certain actions regulated by the current legislation. The whole block acquires characteristics that are the result of these individual behaviours. Emergent properties (Hensel et al., 2010) arise when this happens and consequences affect the urban tissue performance, e.g. wind direction and intensity provoke specific microclimatic conditions that affects building ventilation, inner temperature and comfort in urban spaces.

Towns like Lincoln are benefited with this urban tissue as the blocks tend to be compact. Local climate is temperate dry with quite thermal amplitude. This benefits savings in energy consumption as the thermal mass accumulates heating in winter and prevents overheating in summer. Traditional construction is brick masonry with reinforced concrete roofs.

CONCLUSIONS

Genetic algorithms provide a useful tool to test different alternatives of buildable volumes inside a plot as modules were dimensioned as real architectural elements. They were built considering heights and depths as well as daylight and natural ventilation conditions, regulated by current codes.

In order to widen the scope of this work, GAs can also be used to optimize solar radiation in roofs and façades (Camporeale, 2013) to install PV or solar water collectors. Fenestration can also be optimized by orientation (Camporeale, 2012).

Current legislation on urban design and building restrictions on urban plots deserves a deeper study than fixing height limits, total buildable volume and land occupation. Rules should be implemented according to local conditions as climate, technologies, transportation, energy prices and carbon emissions. They must not be left aside when implementing prescriptive tools as the studied above in order to arrive to undesired results. In our case study, developable density has no influence on the augment of cost transportation as it would have in a suburban neighbourhood. Concentration could be a good tool in a metropolis but not in towns like Lincoln. Tools, as those described in this work, could improve comfort conditions, saving energy to reach a better environment.

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Design Tools for Integrative Planning

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Abstract. *The performance of an architectural object is highly difficult to both define and measure in its complexity since it is integrating a constantly increasing amount of information, from concrete measurable characteristics to the subjective perception of individual users. The question arising though is how to predict the performance of a building and influence the design in order to increase it according to a significantly high number of criteria.*
The presented paper proposes two design tools, both developed and programmed in rhino python for the generation of freeform geometries. The tools are generated for specific tasks, but may be interpreted as exemplary for a way of defining and structuring a design program in order to increase its efficiency. Both tools rely on a computational core that is generally defined and may be fed with as many and different constraints and criteria as considered suitable for the defined task.
Keywords. *Integrative design; evolutionary algorithm; agent-based system.*

INTRODUCTION

Both measuring and changing a design's performance is defined by such a high amount of information that computational methods are of crucial importance in this process. Computational tools may help process a much bigger amount of information and variables than one may be capable to capture intuitively and through classical design methods. The incorporation of digital tools should thus happen as early as possible in the design phase, even at the point of analysing the given task. Still, using the computational power of digital tools in architectural design may prove itself more difficult than in other industries, since a building is usually an individual and very context-dependent object. In architecture time and resources are often insufficient to allow the development of highly performative designs and design methods. Defining criteria of this performance, for an architectural object is a process different for each project, since context- and user-specific factors vary constantly. Therefore generic programs and tools can only cover a very general and unspecific area of the planning process and may only help in the representation and simplification of a design, therefore being insufficient for capturing the complexity of an architectural object.

Numerous established optimisation methods have been incorporated into architectural design opening up a new dimension of solution options and a new freedom degree for designers, but at the same time creating a new extremely complex problem as to how such tools are to be implemented and further developed for the use in design tasks. Many questions arise, such as which method is best suitable for architectural use, how this method is to be translated and implemented, what the limitations are and how these are to be defined in order to increase the creativity of a design and not to define a too strict solution space limit.

Finally the paper proposes a comparison of two acknowledged optimisation tools and their implementation, pros and cons, for architectural design. The purpose is to modify and further develop the known tools and optimisation methods as to find an optimum implementation for specific design tasks.

STATE OF THE ART

Bionics

The traditional top-down design process has already been questioned and a number of bottom-up strategies have been developed and implemented in architectural design having as purpose to include a higher complexity into built design and create more performative and properties-specific results. Bionic processes are one of the main research areas in this development since they draw a parallel between the complexity of nature and architectural building systems. Looking at natural models as examples for specific characteristics and assets of these systems and implementing these into architecture through an abstraction of its principles leads to a differently hierarchized design process and a bottom-up method that includes more information into the early stages of design (Knippers and Speck, 2012). In these processes a specific natural phenomenon (e.g. self-organization), a characteristic of a biological system or a whole biological process (e.g. Evolution), is analysed and translated into design principles.

Evolutionary Algorithms

Evolutionary algorithms are widely used metaheuristic optimization algorithms developed in computer science and mathematics for problem solving (Ashlock, 2006). They are, similar to hill-climbing or simulated annealing, search algorithms meant to look through a solution space for the result of a complex optimisation problem. Developed also by John H. Holland (1995; 1998), as a reference to natural systems, evolutionary algorithms have been of major interest for architectural design from their first appearance in computer science. Their main strength, which designers are trying to make use of, is the capacity of multi-criteria optimisation, therefore searching for a solution that may fulfil more than one chosen criterion. At the same time following the natural system as a model, such optimisation methods show the immense potential that the natural systems have if used as examples in design processes.

The use of evolutionary algorithms has increased in architecture in order to achieve an optimisation of desired criteria, starting with Frazer J.H. in 1995. The final purpose was that their high potential for the built environment should be made use of, since they describe a much more complex system, with similarities to the natural one (Frazer, 1995)

Agent-based systems

A further development of evolutionary theory is the theory of self-organization, both meant to describe and explain complex and chaotic natural systems (Frazer, 1995). The main principle of self-organization implies that an organized system evolves out of a chaotic one only through the interaction of its parts and subsystems, without any higher controlling entity (Camazine et al., 2001). Agent models rely on the definition of a global system through its simple part, a so-called agent. These agents act according to a set of given simple rules, interacting with the other agents and developing complexity and emergent behaviour in the system (Reynolds , 1999) [1]. Examples of such systems in nature are swarms (flocks of birds, schools of fish or ant colonies) where all participating agents follow simple behavioural rules according to their neighbouring agents.

Although in computer science and mathematics agent-based systems are a widely used search algorithm for solving complex problems, in other fields it has been mostly used for simulation. In architecture agent-based systems have mainly offered solutions for crowd-simulation and circulation systems, ensuring an improvement of circulations and spatial arrangement. or particle simulation in animations. Few research projects have used agent-based systems for the generation of form/geometry [2] while these systems often struggle with developing an autonomous non pre-defined system since one of the major difficulties in using agent-based systems is ensuring the convergence of the system in a working solution.

DESIGN TOOLS

Evolutionary Design Strategies

The first presented tool was designed for the generation of a high-rise project. Since the requirements for high-rise buildings present one of the most complex systems in building design, a specific design tool enabling an evaluation and improvement of the tower's global performance was developed.

As intended, the design strategy is based on a computational core that allows multiple use and adaptation to a specific task. In this case a genetic algorithm was chosen for the core as a result of the numerous and complex requirements. A tower's dimensions especially in height have as a result a high number of continuously changing criteria that need to be taken into account when designing a high-rise building. Thus the form of the building has often little flexibility and is very difficult to influence. While the presented project regards the outer form as the result of its inner constraints, the intention is to still have the possibility to choose the degree at which this form is influenced by the designer. At the same time numerous criteria, sometimes contradictory, make it very difficult to even only control these inner constraints so that the outer form often remains the pure functional result of these requirements.

While evolutionary algorithms show great results in optimisation problems with one criterion, their power for architectural design lies in handling more than one requirement and even working through contradictory optimisation criteria. The computational capacity of handling an incredibly high amount of information, comparing and changing this information, makes it very useful for such a complex task. While genetic algorithms can instrumentalise contradictory criteria, the result is not to be seen as an optimum to all chosen criteria but more as a compromise between the different criteria that depends a lot on the value of each criterion that is predefined by the user. It is very important to regard such optimisation results not like in mathematics as the singular and universal solution to a complex problem, but as the specific, task adapted and user dependent solution to one type of definition of the problem.

The process involved in using a genetic algorithm includes three steps: firstly the definition of a geometry generation algorithm, followed by the analysis after certain chosen criteria and the resulting fitness value, and lastly the recombination of the fittest individuals resulting in a new geometry generation. Repeating these steps until a desired fitness value is achieved determines the final geometry of the most successful individual. The geometry generation algorithm describes the first and maybe most influencing step of the genetic algorithm. Determining the freedom degree of the geometry generation algorithm implies setting up a definition that allows enough freedom for the algorithm to utilize as much of the solution space as possible but at the same time ensure that the solutions are fully functioning and don't escape the desired solution space.

For the chosen example the outer shape was modified with each iteration since the purpose was to ensure more flexibility in the form design of skyscrapers and to exploit as many options as possible. One of the major optimisation criteria is minimizing wind loads on the facade of the tower so a more dynamical, organic base geometry, resulting out of lofted curves was chosen. The geometry generation definition includes a various number of flexible parameters, such as the number of curves used, the number of control points and the type of curves used. These are randomly set in the geometry definition so that one generation of individuals includes a set number of completely different geometries (Figure 1).

The second step includes the desired analysis and determination of the fitness value of each individual. This procedure also represents a critical point

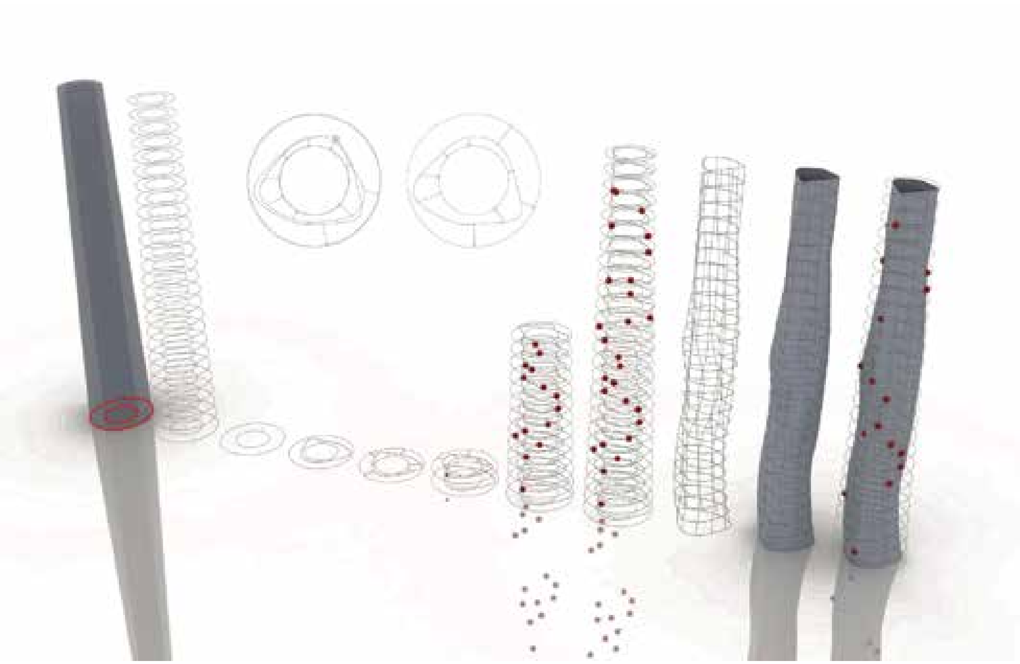


Figure 1
Geometry generation process.

since contradictory criteria cannot be 100% fulfilled but need to be weighted as to how much one criterion shall be fulfilled in comparison to the other ones. Except for choosing and implementing appropriate criteria, weighting these represents another step that strongly influences the outcome of the GA and lies in the hands of the designer. Each specific task requires different analysis criteria and weighting and moreover a strong interdependency between the analysis criteria and the geometry generation process. In the presented case the chosen criteria include a wind load analysis, wind power analysis, solar analysis, area and volume analysis and a number of excluding absolute criteria, such as minimal radii in the facade and the gravitational centre for a basic structural functioning of the building (Figures 2 and 3). The individual weighting of the criteria was performed after numerous tests according to the chosen purpose, not only to create a building as efficient as possible but also focusing on wind loads and wind power in order to achieve as little wind loads as possible on a facade pane but also to use the generated wind power with specifically located wind turbines. This is one example of clearly contradicting criteria in which less wind loads lead to a more stable structure but more wind power results in more energy win. Weighting these criteria against each other could only be achieved after a number of tests in order to understand the algorithms behaviour. In the end a minimal fitness value for wind pressure and suction was chosen to be mandatory so that the wind power generation was weighted less than the load analysis. Still using a parametric definition wind turbines were located in the areas with most wind power so that high energy efficiency could be achieved.

For the recombination and regeneration of new individual generations a stochastic selection method was chosen, such methods being acknowledged and used for an optimal reach of a solution and con-

Figure 2
Fitness values of the fittest Individual.

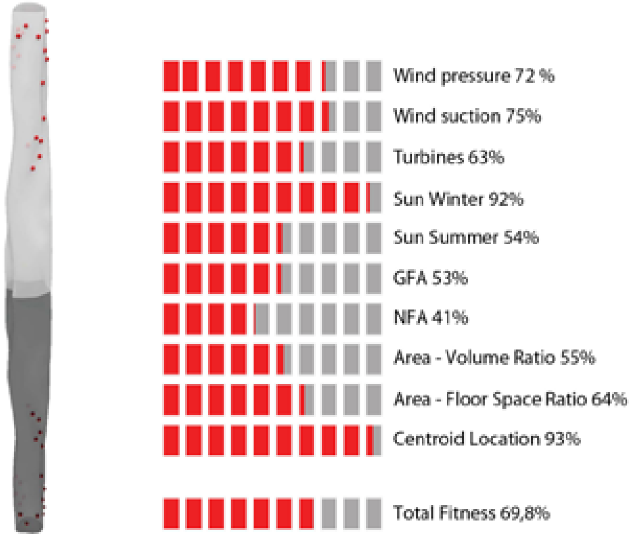


Figure 3
Resulting tower geometry.

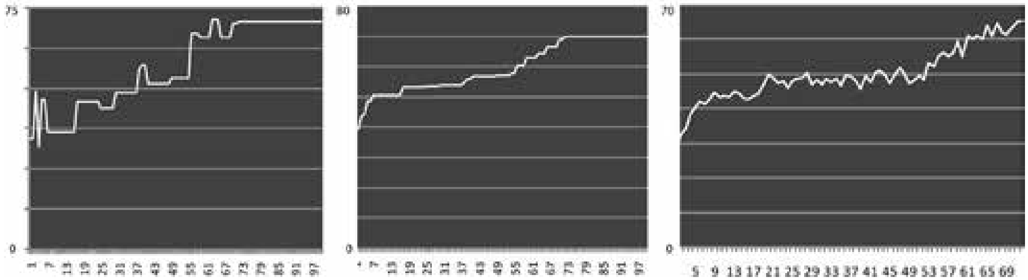


Figure 4
Increment of fitness factors over generations: wind loads, individual, generation.

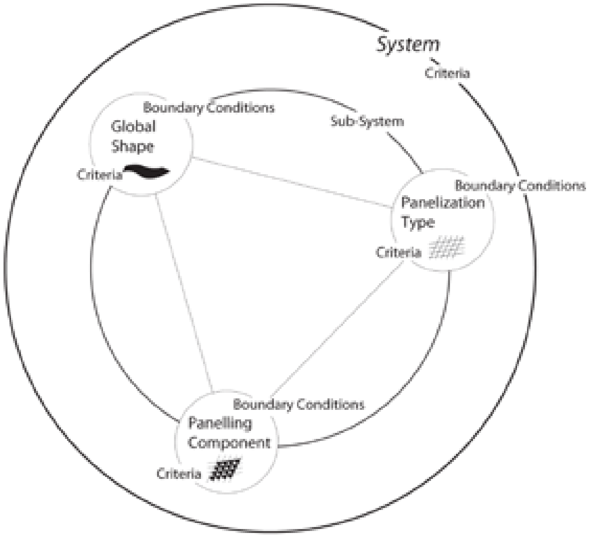
stant increment of the generations' fitness values (Pinsky and Karlin 2011) (Figure 4).

The presented methods have proven to be effective for such a complex task as a high-rise project, but there were still numerous difficulties encountered along the way. One of the greatest challenges resulted to be the black box character and randomness of the written algorithm. While you can track the development of the algorithm and its success or failure, there are no means of intervening throughout the running time or even logically following the process of the genetic algorithm. It proved to be a rather random process in which you could expect that the fitness value of each individual will increase but without any means of fast tracing why or how much it increases. Many tests had to be run in order to manually try out the variable parameters, such as the weighting of the fitness criteria or the geometry generation since it couldn't be easily understood how one value influences the algorithm. While this is part of the power of computational means, of generating designs that cannot be intuitively traced down, it remains a time consuming factor to set up all variable parameters so that a successful result will be achieved. It is a run and result process in which the designer has no capability of interacting with the computational tool he created, it is meanly a tool that needs to run through from start to end and can only then be evaluated through its result. Furthermore, a genetic algorithm needs a lot of adjustments in order to simply provide a result that constantly increases its individuals' fitness and does not converge to a not satisfactory early result. One major point is that while the presented genetic algorithm showed effective results, it is still a linear process which follows a direction (form generation – analysis – improvement) that happens on one hierarchic level and is furthermore based on creating a very high number of random variants that are then compared and analysed. The wish for further research was to break the linearity of the algorithm and create a process in which different hierarchical levels could interact and lead to a result without the need of many variants but slowly adapting to the given requirements.

Agent-Based Process

Based on the knowledge of the evolutionary algorithm developed in the precedent project, a more general and flexible tool was searched in this second approach. A number of critical points discovered while using optimisation algorithms were defined as crucial and created the basis for the second approach. The exact purpose was to create a more flexible tool, with a computational core that could be extended and adapted to a given task through the addition of adaptation criteria and through changing the input constraints. As a major point the wish to destroy the linearity of such an approach and create a process that allows input parameters from various hierarchical levels and the communication between all subsystems of a general system, served as the starting point for this design method. While the evolutionary algorithm allows numerous criteria to be included and considered, it has a clear differentiation between the generating parameters, in this case the geometry generation, and the optimi-

Figure 5
Interaction of subsystems.



zation criteria. The generation is the one adapting to all criteria so the information flow is unidirectional and does not allow other parameters to adapt to the requirements of the generation method. The purpose of the agent-based tool is to allow this flow of information from all input parameters into all directions and create a communication between all participating subsystems, even located in different hierarchical levels.

The chosen task is more general – also in order to exemplarily represent the possibilities of such a method – and is intended to create a roof like grid-shell structure over a given fictional site. The structure is divided into three representative subsystems that are intended to show different hierarchical levels of the general structure and their interdependencies intended to allow a continuous communication between these subsystems (Figure 5).

The first chosen subsystem is the global geometry, representing the freeform surface connected to the predefined support locations. It defines the global shape and appearance of the final built result and is not intended to be only a result of all other requirements and subsystems but set and adapt according to its own constrains and requirements, such as the smoothness of the surface resulting from the angles of the different panels or the structural stability of the global force, curvature and height.

The second subsystem represents the panelling elements, such as triangles or quads through which the global geometry is realized. These have flexible parameters such as shape, or planarity. These requirements set by the designer are meant to inform the other systems while the covering panel itself shall change dimensions and orientation or location according to the requirements coming from the other systems.

The third subsystem describes a shading panel, meant to be representative for any type of facade panel reaching from a simple planar glass pane to a complex shading element. This panel again defines a set of requirements such as planarity, dimensions or orientation. As mentioned before, these systems are simply exemplary and do not cover all complexity of a gridshell structure, but are meant to show the possibilities of such a process.

For the presented example a smooth surface connecting three support locations with certain spa-

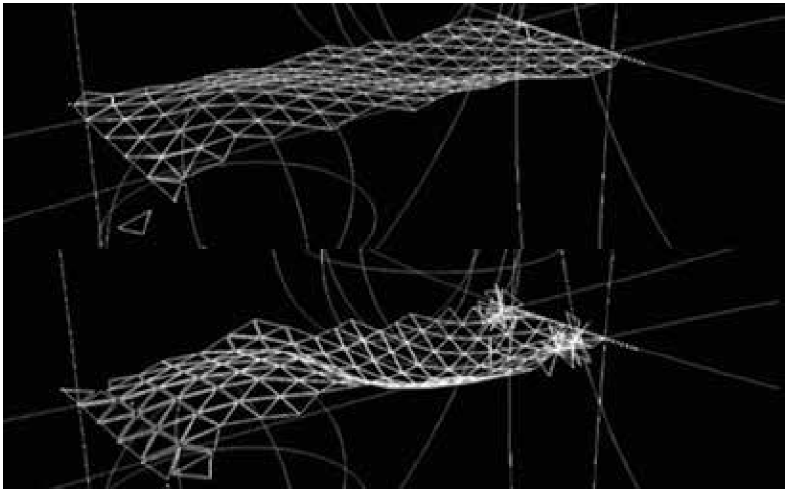


Figure 6
Generated surface without and with geometric structural adaption.

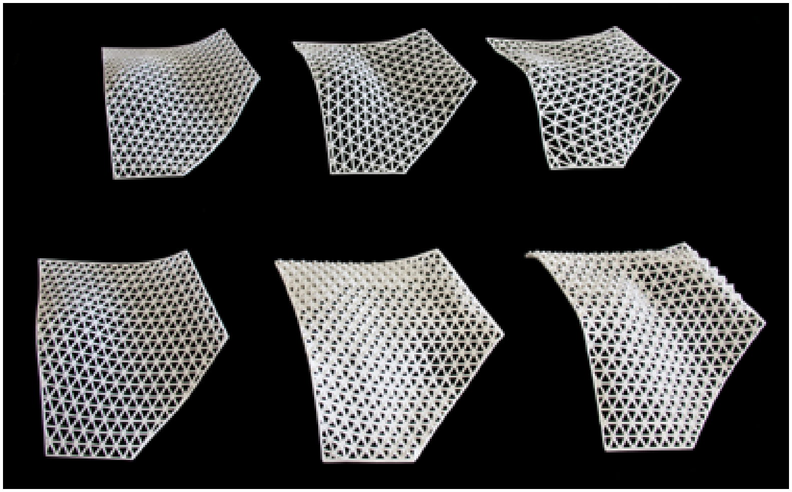
tial limitations, triangular covering panels and a simple shading component were chosen to be implemented. The agent-based system was selected after an extensive research for its capabilities of abstracting and simplifying complex behaviour into simple basic rules. An agent is defined as the smallest part of the system (the division panel) and fed with numerous rules representing all criteria of the participating subsystems. These criteria were all translated into geometric behaviour so that the agent constantly reacts and adapts to the set of requirements enabling a constant increment of these criteria.

Chosen criteria include the smoothness of the surface, dimensions of the beams, the number of beams coming together at a knot, geometric structural behaviour, static behaviour and lighting conditions. The criteria were distributed to represent a specific subsystem or be external criteria in order to show the interdependency and connections of all systems. For example, lighting conditions influence as well the shading pane that changes in size and orientation as the global geometry that is created through the individual triangular panels that focus on achieving an orientation as parallel as possible to the light source. Similarly the static behaviour influences the global geometry that tries to achieve as much double curvature as possible and through this adaptation it defines the position and dimensions of the panels (Paraschо et al., 2012) (Figure 6).

One of the high advantages of this method is the flexibility of the tool and possibility to adapt it to a given task. Since the desire is to create a general tool that may be changed and fed with numerous inputs and criteria, the agent-based system was extremely efficient in allowing such fast adaptions. Each behavioural rule may be added at any time during the process and may influence all defined systems. It has also proven to be very powerful since new criteria can be implemented and tested very fast and the development can be traced simply by watching the agents perform (Figure 7).

Still a number of points have proven to be difficult when implementing such a system. The first question arising is how to abstract such a complex model as a swarm system into a working algorithm for a design purpose. It is of extreme importance how the singular agent is defined, what part of the global system it represents and how flexible it is. Defining the basic agent has the highest effect on the output, since too little flexibility may not ensure any result at all and too much will result in extreme solutions that may not be functioning as built objects

Figure 7
Resulting surfaces after different adaption criteria.



CONCLUSION / COMPARISON

When comparing the two methods the most important fact is to differentiate between the task types that each algorithm can be addressed with. Both algorithms proved to be functioning systems for generating architectural design, but they were focusing on two distinct points. While the genetic algorithm is extremely good in handling a great number of criteria by using the high computing capacities of the computer, the agent-based model is developed to work with less information but create constant connections between this information. The agent-based model's greatest strength is abstracting any type of criteria of any hierarchical system into one equally hierarchized level at which all parts can exchange information. It does not work through numerous variants, created with a random factor, as the genetic algorithm does, but intends to constantly change and adapt in order to improve the characteristics defined in the behaviour of the agent.

One big difference between the presented methods is the option provided by the agent-based model of interacting with the system. The black-box character of the genetic algorithm is broken as the designer can constantly follow the process of the agent-based tool. Future research will focus on the interaction with this system making use of the strength of agent-based systems to react and adapt to any exterior influence at any time. The genetic algorithm is rather a model that strongly depends on the definition of the input parameters and offers one final solution to these options. For tasks where the focus lies on the optimization process and where certain criteria need to be fulfilled as strongly as possible, evolutionary algorithms and their capacity of working with a high number of variants lead to satisfying results. On the other hands, tasks that require more adaption and fast changes in the input would rather benefit from the agent-based tool.

While both systems led to successful results, the main difficulty encountered during the processes was the correct definition of the input parameters. Whereas working through a complex solution space opens up a lot more possibilities than traditional intuitive design methods, this freedom of covering all possibilities is strongly limited by the definition of each constraint, optimization criterion or behaviour definition. Most time and energy flows into defining each parameter influencing the final output and its importance for the global tool. It is often a preconception that making use of the complexity of an architectural object through computational methods automatically opens up an unlimited space of solutions and options. The main issue which further research will address is how to define each component of such a tool as to receive the optimum balance between the freedom degree and the limitations that allow it to be a functional built object.

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Infections

Parametric patterning and material behavior

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Abstract. *This paper covers two workshops that are instances of a research on the feedbacks between parametric patterning and material behavior. Infection sets the conceptual background of these workshops utilizing pattern deformations as a generative technique. Gridal Infection workshop focus on real-time dynamic patterns while Reflex Patterning workshop integrates material performances to this exploration.*
Keywords. *Parametric patterning; material behavior; prototypes; fabrication; dataflow.*

INFECTIONS: GENERATIVE DEFORMATIONS VIA PATTERNING

Patterns have been instruments of analysis and research in various disciplines, from social sciences to computer science, mathematics and biology. Gleiniger and Vrachliotis (2009) state that the pattern concept previously defined as a structural system of order began to gain a new complexity and momentum in the light of cybernetics and system theory. Reflections of these studies with the triggering of computational tools have shifted the notion of pattern in architectural design realm. The classical notion of pattern as, formal, ornamental, decorative and geometric orders of repeating shapes has turned into the contemporary conception of pattern as *structural, sequential, distributed, or progressive* systems of repeating units or processes (Garcia, 2009). Meanwhile parametric design tools have become essential to think and act on this broader sense of patterning by accelerating and expanding space of possibilities through variation and diversity.

This paper covers two instances of a research that focus on the feedbacks between parametric patterning and material performances within a context. **Infections** is a series of workshops in which we study methods of interaction in-between digital and material to reveal the potentials of the context. The conceptual background of infection -even if sounds like an invasion- is a challenge and springboard for students to explore potentials via deformation processes. This concept provokes them with subthemes such as *immune system, recovery, metamorphosis and becoming. The* process begins with *pattern recognition*, an attempt to observe and perceive existing orders of *the context called host body*. Next, students are encouraged to manipulate the host body in a creative way utilizing *pattern deformation techniques.* Therefore, infection is both the metaphor and the method of these deformations, while the host body represents a pre-defined system and the physical context to be *infected*.

In the first workshop named **Gridal Infection,** this manipulation is studied by projecting *real-time dynamic patterns* on the glass-brick walls of the faculty building at YTU.

The second workshop, **Re-flex Patterning** is

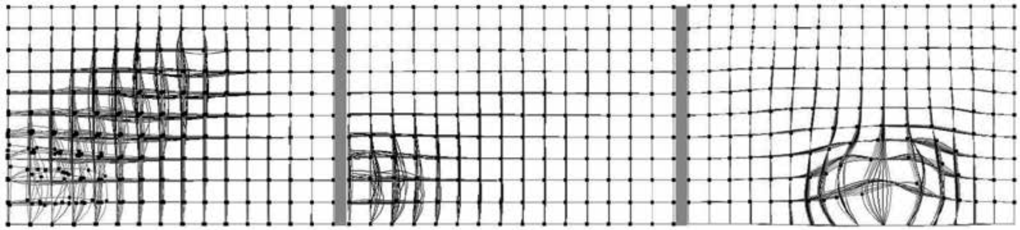

Figure 1
FiberGrid; Screenshots.

based on the correlation of the digital with the physical via parametric patterning techniques and a composite material system.

The third and last step in the ongoing research will be pushing the limits through the fabrication processes. Parametric patterning and CNC molded tiles will be explored as a case study for the future workshop.

In following sections, details of the first two workshops are explained, concluding with a discussion on outcomes.

WORKSHOP 1: GRIDAL INFECTION

This initial workshop focuses on the abstract notion of grid, sampled from an existing 16x11 unit glass brick wall, *the host body.* Students are asked to articulate its formal (*grid / pattern / tessellation / reference*), performative (*transparency / light / structure / function*) and tectonic (*ambient / kinetic / aural*) properties. On the early phase, three groups of students hunted concepts "lesion, plasma and fibergrid". Then, they are asked to develop their projects by creating *parametric deformations,* utilizing real-time interactions with the context. Students with no previous skill on parametric design are introduced with Grasshopper for dataflow parametric modeling and Firefly add-on for interaction design. They ended up with three dynamic patterns, superimposed to the existing wall. The semi-opaque material of the wall created a surreal-animate vision and an apopohenia kind of feeling for the viewers. As an educational goal, the attempt was not to create an eye catching media-wall but to introduce students with digital toolsets necessary to make them think of feedbacks in-between the digital and the physical during the design process.

In the final application, visual outputs are projected on the host body, aligned to its existing grid. Below are three student projects that are the products of this three day introductory workshop.

FiberGrid

Students considered the host body as a *dead tissue* of an organism, resembling the wall as a *standing idle* and *reckless* element to its environment. In order to *revitalize* it surrounding sound is considered as an *injection* that changes the inner structure of the organism and transforms the grid lines into curvilinear *fibers.*

Above concept of **FiberGrid** is realized by constructing a grid out of interpolated curves (Figure 1). Surrounding sound is captured and used as a real-time input that bends the curves. The change in sound level affects the process, creating temporal variations. Finally, a history enabled algorithm captures sequences of this process, creating *waves* of fibers (Figure 2). As it is a recursive algorithm, it responds concurrently, getting faster / slower and more / less fibrous while the surrounding sound level rises / lowers (Figure 3).

Lesion

In this project, the grid is considered as cellular forms packed together. The wall represents an absolute body, in which an infection causes various challenges, and activates an *immune system* as well. The struggle between infection and the immune system creates **lesions eventually** (Figure 4). This concept resembles infection as a distortion on the regularity of the wall. Irregularities of the surrounding factors,

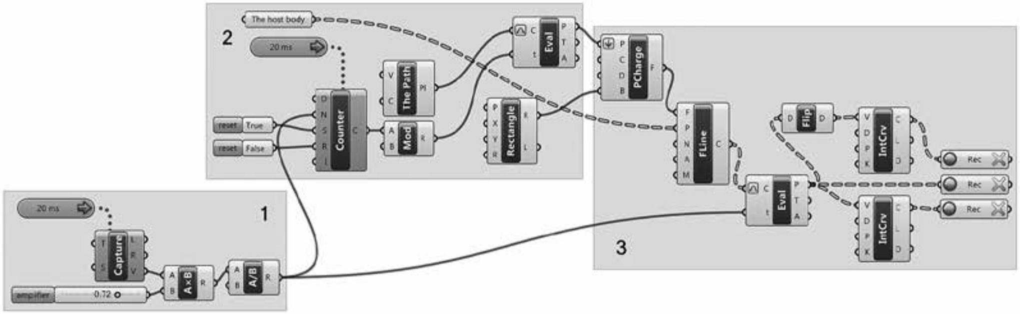

Figure 2
FiberGrid; Dataflow diagram composed in Grasshopper. Cluster 1 captures surrounding sounds; Cluster 2 develops a square grid out of curves; and Cluster 3 generates force field deformations to the curves, based on the sound level.

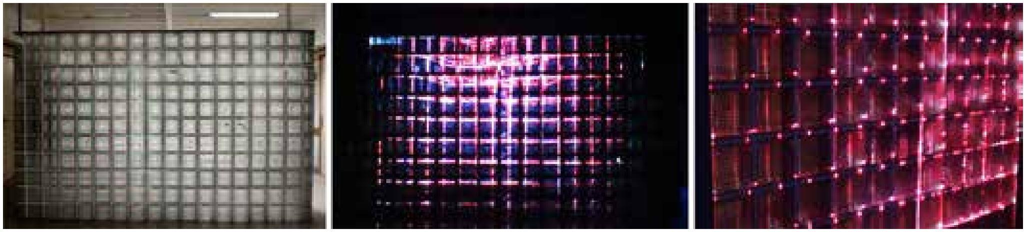

Figure 3
FiberGrid; Application photos. 'The Host Body' is on the left.

such as the movements of people around causes pattern deformations. The host body gets infected when someone gets closer to it, but eventually a time-based *recovery* process begins.

This concept is realized by implementing a history based truncation process on a regular grid (Figure 5). The truncation is associated with the vectors of surrounding motions, captured by a webcam in

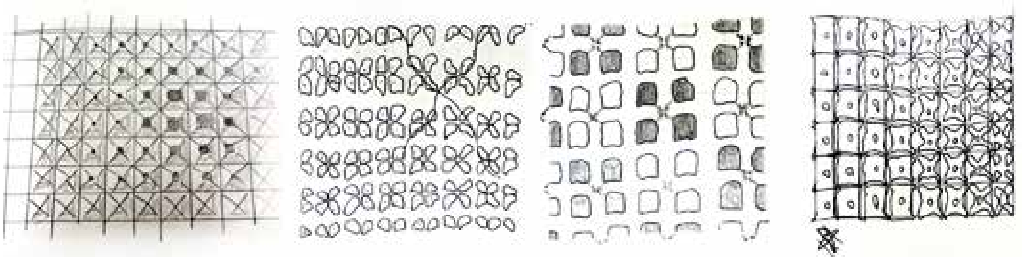

Figure 4
Lesion; Student sketches.

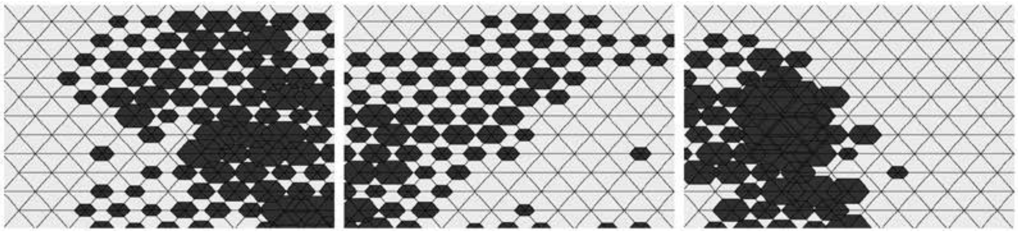

Figure 5
Lesion; Screenshots.

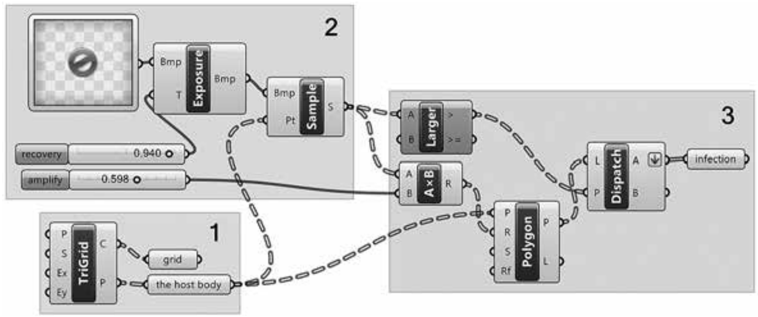

Figure 6
Lesion; Dataflow diagram composed in Grasshopper. Cluster 1 creates a regular grid to be infected; Cluster 2 captures the webcam input; and Cluster 3 processes this data according to the design intentions, creating polygonal shapes on the grid.

Figure 7
Lesion; Application photos. 'The Host Body' is on the left.

real-time. There are parameters such as recovery and immune system in the dataflow diagram (as seen in Figure 6) that function as a temporal deformation returning to its initial state progressively. In the final installation, various regular grids (square and hexagonal) are tested with an infection caused by people around (Figure 7).

Plasma

In this project, the host body is considered to be infected by high fever and pressure, changing its solid phase into plasma. The solid molecules represent the strict order of the grid on the wall, while the plasma represents a more flexible order, sensitive to its surroundings. The real-time deformation input was a similar one with Lesion, including a webcam capture. Distinctively, this project aims to capture not all of the small details of the surrounding, but the average motion, searching for focal points of movement. Students argued that this transformation of the glass brick wall to plasmatic body makes it more interactive with other bodies around it.

In this project, students' conception (Figure 8) is extended into a geometric solution based on metaballs (Figure 9). After various experiments on the reactions of metaballs, a grid-based deformation is chosen (Figures 10). When a person comes closer to the wall, its motion creates focal points. Eventu-

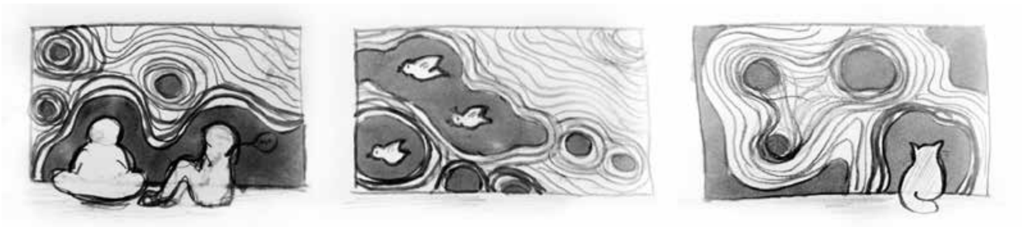

Figure 8
Plasma; Student sketches.

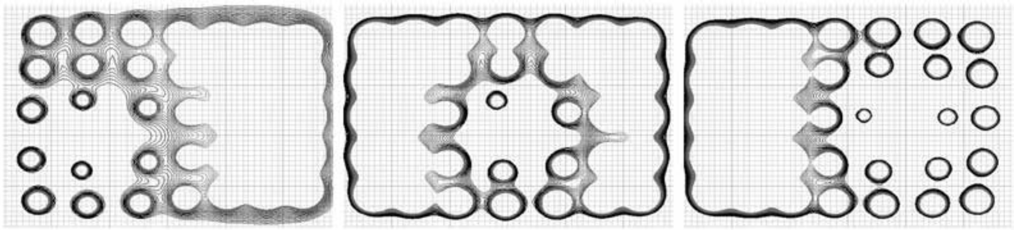

Figure 9
Plasma; Screenshots.

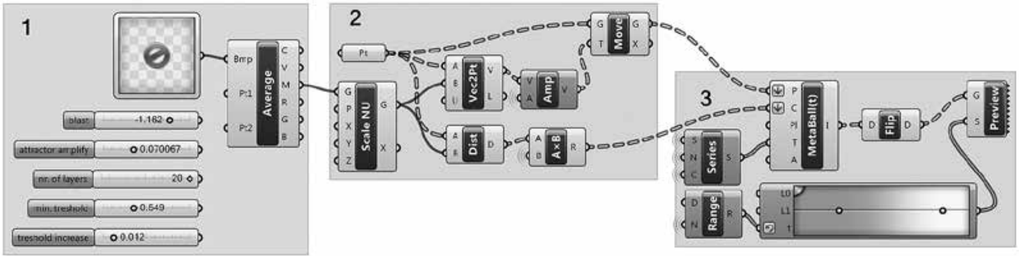

Figure 10
Plasma; Dataflow diagram composed in Grasshopper. Cluster 1 collects all necessary data including the webcam; Cluster 2 calculates a vector deformation on a regular grid; and Cluster 3 creates a serie of metaballs.

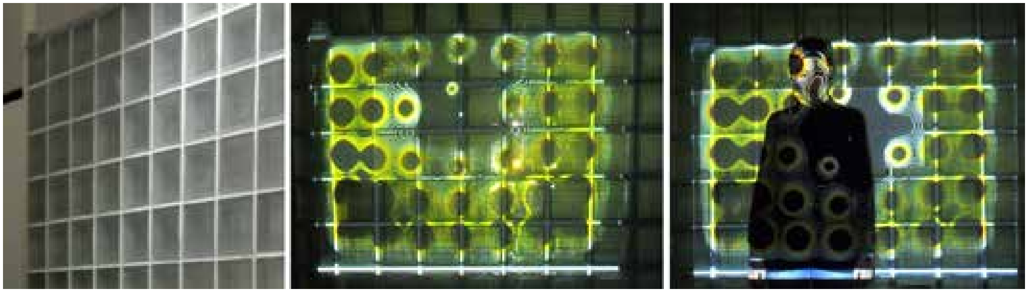

Figure 11
Plasma; Application photos. 'The Host Body' is on the left.

ally these points become blob centers that react and combine into larger blobs (Figure 11). A time-based algorithm captures sequences of this process, creating superimposed metaball variations.

WORKSHOP 2: RE-FLEX PATTERNING

In the second Infections workshop, the host body was the gallery hall of the faculty building at AİBU, a passive void waiting to be activated (Figure 12). The regular pattern dominating that body was the structural grid of columns and beams that is reference to all the details around it such as floor coverings, lightings etc. In this workshop students are encouraged to think on sub concepts of infection, recognize existing patterns of the hall and transform that inert void to a reacting body.

Within this three-day workshop, we worked with 30 students and introduced them with digital techniques of pattern-making and pattern deformation using Grasshopper. We discussed on how they could use parametric modelling to deform a grid based pattern.

The composite material system proposed for the workshop was a combination of flexible and soft materials (textile or bubble wrap) with a stiffer but lightweight plate material (5mm. foam boards). Soft material is to be covered with foam boards in both sides with nuts and bolts to explore its composite

Figure 12
Re_Flex Patterning; 'The Host Body'.

material behavior. Students were required to propose a patterning that controls the behavior of this composite material with the help of the re-flexing performances.

Prototypes
On the first day, we discussed on concepts of infection and the context. 5 groups of students presented their proposals via diagrams and drawings. They focused on changing parameters and dynamics such as daylight, circulations, gatherings, vistas and proposed concepts as molecules, fluid flows, colorizing etc. We wanted them to construct their first material prototypes by 2 m X 2 m via various methods of patterning. The next morning students installed their physical prototypes to the hall to observe the reflexes of the material and reactions of the host body. Each project was unique to explore various material behaviors using regular, irregular and associative patterning (Figure 13). Students chose the project that proposed a canopy formed by patterns of circulation .This project was able to control the macro-form as a self-regulating surface.

Final
The last step was working on patterning of the chosen project, and is developed with the guidance of instructors. At the application phase, 1600 individual polygonal elements are coded and laser-cut from foam boards, attached to the textile with nuts and bolts (Figure 14). The product of the workshop was two canopies of 1,5m. by 5m. in size. The emergent

Figure 13
Re_Flex Patterning; Initial prototypes, testing the composite material with various tessellations.

Figure 14
Re_Flex Patterning; Third and final day, fabrication.

performances of this product could only be experienced when these surfaces were installed in the gallery hall via *flexing* them with the help of steel cables (Figures 15, 16 and 17). Students were excited with a feeling of both familiarity and alienage of this product, mentioning that the passive void is becoming an-other living body.

CONCLUSION

Contemporary trend of the computational design education is grounded on an integration of domains such as fabrication technologies, material studies, and generative techniques. This requires not only an intuitive handling on digital tools and methods, but also an experience on material and production constraints simultaneously.

Patterning emphasizes a material shift in the generative side of the digital paradigm, and a geometric shift in the material side, as well. The study presented in this paper is an example of the integration between digital tools and material practices by implementing pattern deformation as a synthe-

Figure 15
Re_Flex Patterning; Third and final day, installation.

Figure 16
Re_Flex Patterning; Final project.

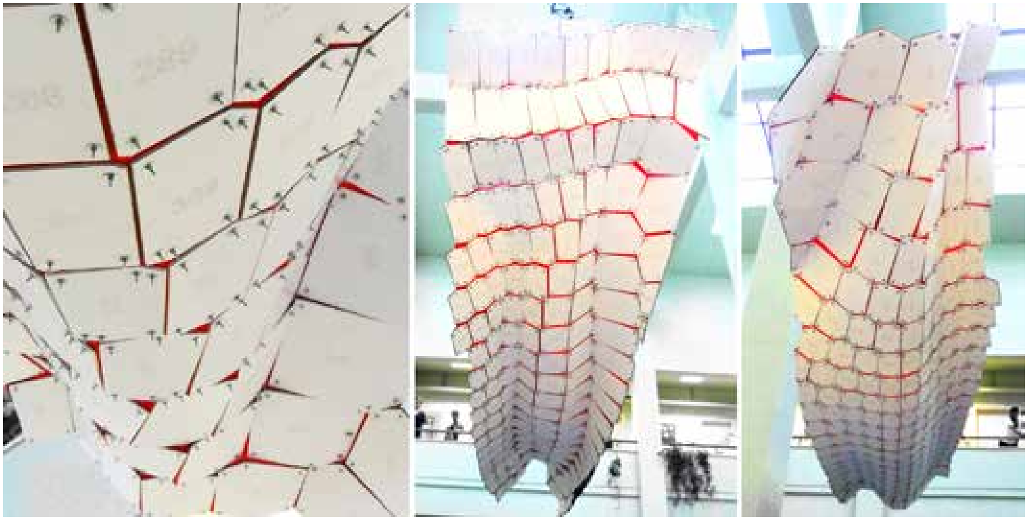

Figure 17
Re_Flex Patterning; Final project.

sizer. Such integration liberates students from passive and formal search of an on-screen parametric modeling, familiarizing them to a more practical and sophisticated body of knowledge about the physical becoming itself. Nevertheless, the articulation and reconstruction of patterns help pedagogical objectives as they promote temporal but instant, explicit but unstable nature of design exploration.

ACKNOWLEDGEMENTS

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Algorithmic Engineering in Public Space

Patterning strategies for a plaza paving

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Abstract. *The paper reflects on a relationship between an algorithmic and a standard (intuitive) approach to design of public space. A realized project of a plaza renovation in Czech town Vsetin is described as a study case. The paper offers an overview of benefits and drawbacks of the algorithmic approach in the described study case and it outlines more general conclusions.*
Keywords. *Algorithm; public space; circle packing; optimization; pavement.*

PUBLIC SPACE

Instead of the embodiment of a static order more and more a city is considered to be an ever changing organism. Over few decades, architects have to cope with new concepts of space imposed by global markets, the Internet, ballooning population figures, social isolation, and environmental crisis. Philosopher Peter Sloterdijk argues in his article *"Foam City"* that architectural designs have been always integral to establishing the society.

City vs. Society

The article focuses on the Fête de la Fédération of July 14, 1790, celebrated on the first anniversary of the storming of the Bastille. The author argues that the architectural staging of this spectacle served to generate an embodiment of the nation, enhanced by affective and acoustic measures. While the article is mainly concerned with the architectural technologies of politics related to the French Revolution, it also points beyond this specific historical case and briefly indicates how 20th-century fascisms used techniques that were prefigured by 18th-century French inventions. In both of these cases monumental and vast public spaces allowed the gathering of the crowd and assembly of a national collective.

Foam City

The current nature of the human environment is defined by the fact that nature and human action can no longer be separated. Technology and nature are considered to be all part of a network; a whole that cannot be managed by simple urban planning strategies.

Sloterdijk describes the city as a Foam City: *'The co-isolated foam of a society conditioned to individualism is not simply an agglomeration of neighboring (partition-sharing) inert and massive bodies but rather multiplicities of loosely touching cells of life-worlds'* (Sloterdijk 2006).

In other words the idea of the collective society has disappeared and was replaced by the society that resembles the foam, where the individuals are clustered in co-isolated groups. In these co-isolated groups individuals share their interests and opin-

Figure 1
The original setting out of the circles within the plaza boundary.

ions. Therefore the city and public space can no longer be designed for a massive collective but rather for an ever changing multiplicity.

PROJECT GOALS

Several years ago, we were approached by Moba architectural studio to collaborate on a refurbishment of a medium sized town in our country. The original design was based on Sloterdijk's Foam City metaphor. We were commissioned to develop a method (algorithm) that would set out a layout of hundreds of concrete circles in the surface of the refurbished plaza while reflecting Sloterdijk's observation of the society in his article *"Foam City".*

The assignment consisted of two rather independent steps. The first step was the functional analysis of the square and development of a patterning strategy that would initiate various activities to happen in the public space. There was hardly any social interaction happening in the square beforehand and the entire space was used mainly as a communication corridor. By developing a right patterning strategy we aimed to invite as many social groups to interact in the plaza.

The second step was to develop the algorithm that would guarantee that all technical requirements are met. There were seven sizes of the concrete circles with diameter ranging from 1.2 to 4 meters. No two circles could intersect with each other and also with multiple other objects/obstacles. Furthermore the minimum continual asphalt area among the circles could not be less than 0.5 m^2due to given construction limitations.

METHODS

Input, brief

Early in the process we realized there is a strong relationship between any algorithmic method and the designed pattern. The original design (an outcome

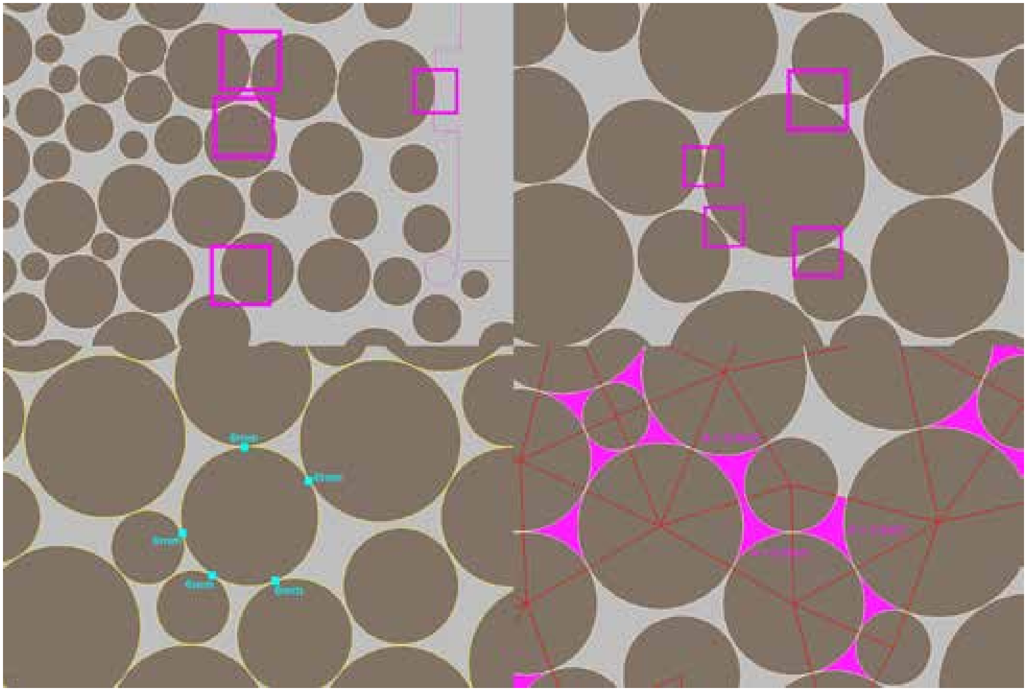

Figure 2
Technical requirements for optimization.

of an architectural competition) was based on a random distribution of circles with the highest density in the centre of the plaza (Figure 1). The paving pattern was created intuitively by the architects. Our task was to optimize the design with as little intervention as possible.

Technical requirements

We used a simple circle packing algorithm based on collision detection and an iterative approach. The algorithm ran through the randomly generated circles and in every round checked for several conditions derived from the brief (Figure 2).

1. If any of the circles collided with the boundary of solved space it was moved away in the opposite direction.
2. If any two circles were closer than 6 millimeters to each other both of them were moved apart in the opposite direction.
3. If the concave residual space defined by any three circles was smaller than 0,5 m^2 (gap smaller than 50 millimeters was considered as closed) all three circles were moved apart.

The process usually took about one hundred iterations to optimize the circles. Visual aids to mark any possible collisions were scripted in to help to remove possible dead end suboptimal results.

Functional analysis of the square

Having met the technical part of the brief early in the work process, we started to question the functional quality of random distribution. The architects did not have any means of designing layout of almost five hundreds circles other than random distribution with intuitive gradient density. Our motivation was to propose a better way of working with such a high amount of design elements and still be coherent with the original design brief.

	Tiles - small size	Tiles - medium size	Tiles - large size	Tiles density	Blacktop continuity	Pattern x Purpose
Communication			X		X	
Public space	X	X	X	X		
Commerce	X	X				
Auditorium		X	X	X		X
Restaurant	X			X		X
Relax	X	X				X

Table 1
Relation of the public space to the pavement quality.

We analyzed the public space and defined several qualities of the pavement that we wanted to address in a new generator (Table 1). For example, spots with more and faster traffic would be defined by bigger and less dense circles (the asphalt is easier to walk and cycle on), spots that were supposed to become quiet rest areas were defined by a high density of the whole range circles, spots to slow down on (such as entranced to public buildings) were defined by a high density of smaller circles.

With such an approach we were able to compose a colored gradient map that served as a layout

Figure 3
Gradient map of different qualities of the public space.

Figure 4
Realized first stage of the project.

generator (Figure 3). However, this algorithmic driven design method was perceived by the architects as something uneasy to control and was not developed further.

CONCLUSION

Without an algorithmic approach it would not be possible to handle a project of this size within the short amount of time given to the project. The algorithmic approach not only helped to optimize the setting out of the circles but was essential for production of final project documentation and for laying out the concrete circles on site (Figure 4).

The failure of the approach was inability to change the rather simple definition of random distribution and gradient density of the circles. The designers were not comfortable with passing any control to an algorithm and with dual authorship (as described by Carpo (2011)). It is disputable whether there was any control (other than intuitive visual) at the first place.

In a general, yet similar, case (urban paving pattern), early design stage algorithmic tools capable of gathering and manipulating vast range of design information would help the team do devise a better and more **functional** design. In that case, an "information engineer" should play a substantial role in the design team similar probably to a role construction, civil or technology engineers play during a standard building design process.

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Integrating Computational and Building Performance Simulation Techniques for Optimized Facade Designs

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Abstract. *This paper investigates the integration of Building Performance Simulation (BPS) and optimization tools to provide high performance solutions. An office room in Cairo, Egypt was chosen as a base testing case, where a Genetic Algorithm (GA) was used for optimizing the annual daylighting performance of two parametrically modeled daylighting systems. In the first case, a combination of a redirecting system (light shelf) and shading system (solar screen) was studied. While in the second, a free-form "gills surface" was also optimized to provide acceptable daylighting performance. Results highlight the promising future of using computational techniques along with simulation tools, and provide a methodology for integrating optimization and performance simulation techniques at early design stages.*
Keywords. *High performance facade; daylighting simulation; optimization; form finding; genetic algorithm.*

INTRODUCTION

The building's skin plays the main role in delivering natural daylight to indoor spaces. Performative façade design can significantly improve the indoors visual and thermal conditions, which in turn, improves the quality of life and work environment by creating productive and appropriately lit spaces. Building skins, therefore, shouldn't be just designed for its aesthetic aspects but also as a functioning element in the building.

Building Performance Simulation (BPS) tools are broadly used for achieving designs that have better impact on the users and the environment. While simulation tools are effective in testing and evaluating different designs, it becomes harder when evaluating numerous solutions. Simulation engines usually take a considerable amount of time for each solution. Therefore, it is more practical to consider using optimization tools that can arrive to an optimal solution without the need of testing all possible ones. This paper investigates the ability of integrating computational and simulation tools for design problems with different levels of complexity. The methodology proposed in this research employed a simple Genetic Algorithm for optimizing the daylighting performance of parametrically modeled office building facades.

Genetic Algorithm and Daylighting Performance

A traditional optimization scheme is an algorithm which finds the minima or the maxima of a given function, typically known as the objective function. The objective function may depend on any number of parameters and any combination of parameter values within the defined search space is considered a feasible solution. The optimal solution will be the feasible set of parameters which minimizes (or maximizes) the objective function. A problem will not necessarily have one unique solution. It may have no optimal solutions at all, a finite number of solutions, or an infinite number of solutions, which can be defined as a more specific subset of the search space (Papalambros and Wild, 2000). For problems which involve simulation engines heuristic search algorithms are usually used and considered an appropriate choice. These algorithms are considered heuristic as they depend on trial-and-error approach and as such, they are not guaranteed to converge to true optimal solutions. However, most of these algorithms do find solutions which are very close to optimal (Gagne and Anderson, 2010).

The Genetic Algorithm (GA) is an algorithm which works by mimicking the process of natural evolution and was first introduced by Holland and Reitman (1977). It is one of the most commonly used heuristic search techniques, and has been applied to many types of architectural problems. Genetic algorithms had been successfully used in several research works for enhancing daylighting performance. Tsangrassoulis et al. (2003) presents a technique for the design of slat-type blinds based on the relative light intensity distribution under a uniform light source. The technique used a genetic algorithm in order to evolve the design according to a set of parameters. Another research investigated altering free-form ceiling geometry design to optimize indoor daylight uniformity ratios (Rakha and Nassar, 2011). Other research works focused on optimizing the facade design and openings to achieve better daylighting levels and comfort (Torres and Sakamoto, 2007; Gagne and Andersen, 2010; Portugal and Guedes 2012).

Although several investigations had been previously carried out on using genetic algorithms for performance optimization, most of the previous researches were made on simplified problems, such as window positions or shading device parameters. This paper aims to investigate the proposed methodology under two conditions. A simplified guided-search case, where several cases and parameters that are predicted to offer good results are being optimized. The aim in this case is to find a better solution from numerous good solutions, in other words an optimal solution. Conversely, the second case investigates an exploratory search that has no guides to start with. A free form façade design was optimized for better daylighting performance. A larger number of choices and parameters were also introduced in order to investigate the methodology's ability in problems with a larger pool of solutions. The aim of the second case is not mainly reaching an optimal design but instead to discover the potential of using the proposed methodology in more complex contexts.

METHODOLOGY

A typical side-lit office room space was selected for investigation. The case study was chosen to be located in the city of Cairo, Egypt (30° N- 31° E). The office is room is a 4.00m wide by 6.00m deep rectangular space, with 3.00 m clear height. The office space was assumed to have a 6 mm double glazed window that is 3.60m wide and 1.80m high (Figure 1 and Table 1). The space was considered to be on ground level with a free horizon and no obstructions. Ground reflectance of 20% was assumed. At first, the base case was modeled and its annual daylighting performance was observed. Afterwards, Genetic Algorithm (GA) was used for optimizing the annual daylighting performance of two parametrically modeled cases. In the first case, a combination of a redirecting system (light shelf) and shading system (solar screen) was added to the base case. While in the second, a free-form "gills surface" façade was also optimized to provide acceptable daylighting performance.

Daylighting Simulation Methodology

Simulation was conducted using the Diva-for-Rhino V 2.0, a plug-in for Rhinoceros modeling software. It was used to interface Radiance and Daysim for annual simulation and illuminance computation (Reinhart et al., 2011). Simulation was conducted annually for weekdays from 8:00 AM to 4:00 PM which represents a typical Egyptian eight-hour working

Figure 1
Isometric view of the studied office room.

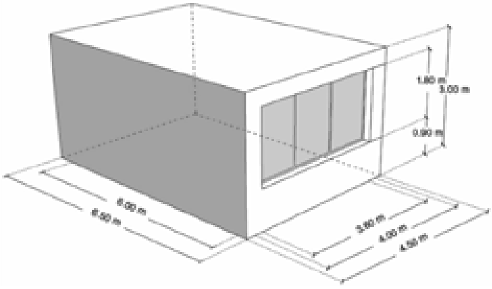


Table 1
Dimensions and properties of the tested office space.

Space Dimensions and Materials		
Floor level		Zero level
Space dimensions (m)		4.00 * 6.00 * 3.00
Walls	Reflectance	50%
	Material	Medium Colored
Ceiling	Reflectance	80%
	Material	White Colored
Floor	Reflectance	20%
	Material	Wooden Floor
Window Dimensions and Material		
Width (m)		3.60
Sill (m)		0.90
Lintel (m)		2.70
Glazing		Double clear glass 6 mm (VT = 0.647)

time. The reference plane on which daylight performance was simulated contained 117 measuring points in a grid of 0.5m* 0.5m, at a working plane of height 0.8 m. Measurements that were found equal or higher than the recommended minimum illuminance value for an office space, 500 Lx, were considered "adequate" (IESNA, 2000). Daylight Availability a Dynamic Daylight Performance Metric (DDPM) was used for evaluation. It presents three evaluation criteria: "daylit" areas (the adequate areas), for spaces that receive at least half the time sufficient daylight compared to an outside point, "partially daylit" areas, which are below useful illuminance and "over lit" areas that provide warning when an oversupply of daylight (10 times target illuminance) is reached for at least 5% of the working year. Analysis criteria for Daylight Availability adopted in this paper assumed that the designs that achieved equal or more than 50% "daylit" areas and at the same time minimum values for "over lit" and "partially daylit" areas were considered efficient.

Parametric Modeling and Optimization Methodology

Generative designs and parametric models were modeled using Grasshopper a plug-in for Rhinoceros modeling software. Grasshopper allows changing the model parametrically where each design parameter is directly linked to a floating-point slider that determines its value. Galapagos, an evolutionary solver, is a GA optimization tool used within the platform of grasshopper and was used to control and modify the different parameters. During the GA process, a set of initial solutions (a generation/population) is generated at random. Each solution is sent to DIVA for conducting Daylight Availability simulations. The results are then processed to calculate the daylit area percentage using a fitness function that is expressed as:

$$F(x) = N' / N \quad (1)$$

where N is the total number of measuring nodes, and N' is the number of nodes which receive at least half the time sufficient daylight.

Solutions that result in good performance are used as "parents" for a new generation. Parent members are combined using a genetic operator called crossover to create a new generation of "child" members which have characteristics of the parents. Since this new generation is based on the best performing solutions in the previous solutions, it is assumed that some members of the new generation will perform better. Once evaluated, again the good performers are used as parents while the poor performers are discarded. The cycle continues until a number of generations have been completed. In this research a simple GA with 20 genome/generation was used. Optimization continues until an optimal solution is obtained and remained unsurpassed for continuing twenty generations (Stagnant Generations) (Figure 2).

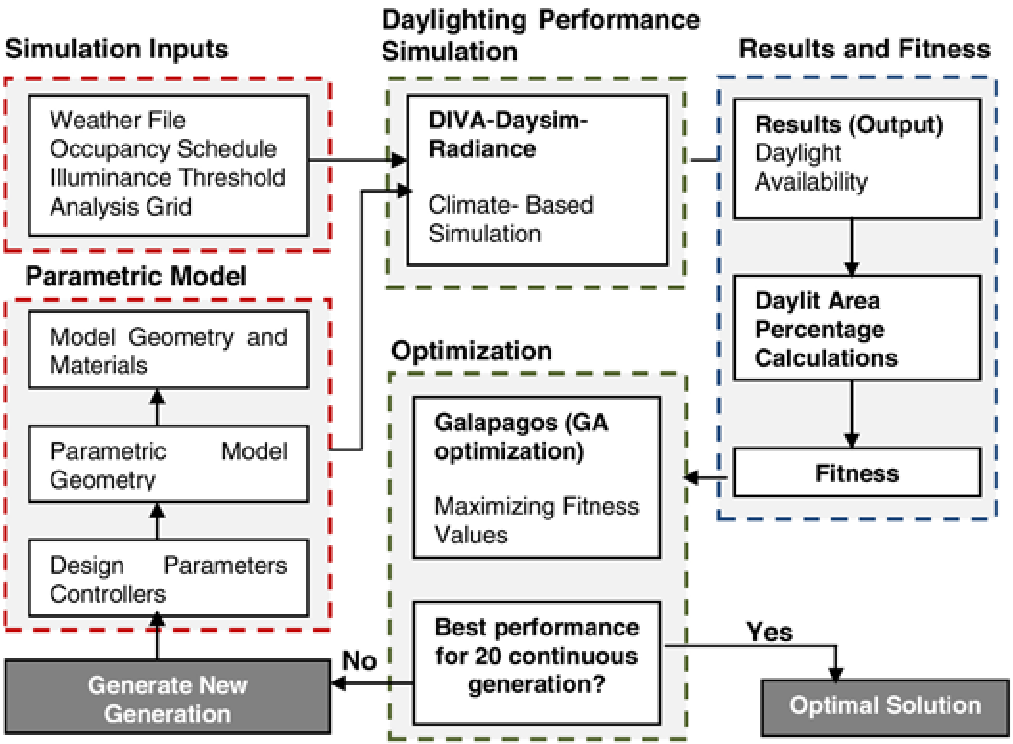


Figure 2
Optimization methodology diagram.

BASE CASE SIMULATION RESULTS

Daylight availability was analyzed for the base case facing the South and the East orientations. Both South and East facing spaces were subject to the penetration of the direct sun. Overlit areas reached 43% in the South and 42% in the East. However, no partially daylit areas were anticipated in South oriented office space where daylight area reached 53%. In the East faced room, 13% of the space were found to be partially daylit (Table 2). The main challenge, therefore, is to eliminate the overlit areas without a significant increase in partially daylit areas.

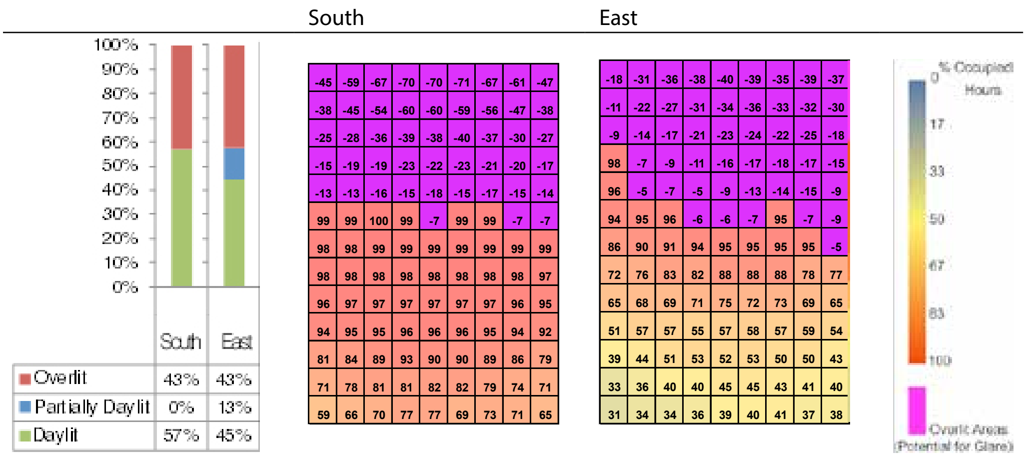
FIRST CASE STUDY: LIGHT SHELF AND SOLAR SCREEN COMBINATION

In previous research work by Sherif et al. (2012), solar screens were found to be highly effective in eliminating the overlit areas. However, in many cases that came with a drawback in the overall performance due to the increase in partially daylit areas. Combining the solar screen with light shelves was found to achieve better results. In this case combining solar screens and light shelves was examined. The design parameters of both systems change according to the results obtained from previous research works (Sabry et al., 2012). The parametrically modeled cases had six different changeable parameters shown in Table 3. Overall, the number of resulting possible designs exceeds two thousand possible solutions.

Daylighting performance optimization results

An optimal design was obtained and the performance reached 64% in the sixth generation, where

Table 2
Daylight availability distribution for the base case in South and East orientations .



a 1:1 (H: V) screen with 90% perforation and 50° VSA was combined with a 120 cm, 10° rotated light shelf. It remained the best solution for the next twenty generations. However, several designs also went far beyond the performance of the base case (45% daylit area). Moreover, all the proposed solutions had minimal overlit area percentages which didn't exceed 7% of the whole space area and several cases succeeded in entirely eliminating the overlit area. Figure 3 shows the simulation results after the 26 generations. It's noticed that the optimal solution was reached at an early stage within the first six generations. The process afterwards wasn't successful as the coupling with new solutions resulted in worse solutions while the optimal solutions kept unmatched. Table 4 illustrates the best results obtained from the optimization process.

SECOND CASE STUDY: FORM FINDING

Form-finding can be described as a process of discovery and editing (form emerges from analysis). Extreme form-finding is not fully architecture but more applied engineering as form exclusively determined by function. In this case study a free form daylighting system was proposed. Similar to the previous studied case, this system combines a redirecting and shading techniques, however the form is more organic and fixable. A "gills surface" was modified to be used as a shading devise in the lower part of the window and as a light shelf in the upper part. Gills

Table 3
Parameters considered for the first case.

Solar Screens

Parameter	Possible values
Vertical Shading Angle (VSA)	70°, 60°, 50°, and 40°
Perforation	90%, 80% and 70%
Aspect ratio (Horizontal: Vertical)	1:1, 2:1, and 4:1

Light Shelves

Parameter	Possible values
External light shelf depth	60 cm, 80 cm, 100 cm, 120 cm
Internal light shelf depth	30 cm, 60 cm, 80 cm
External light shelf rotation angle	0°, 10°, 20°, and 30°

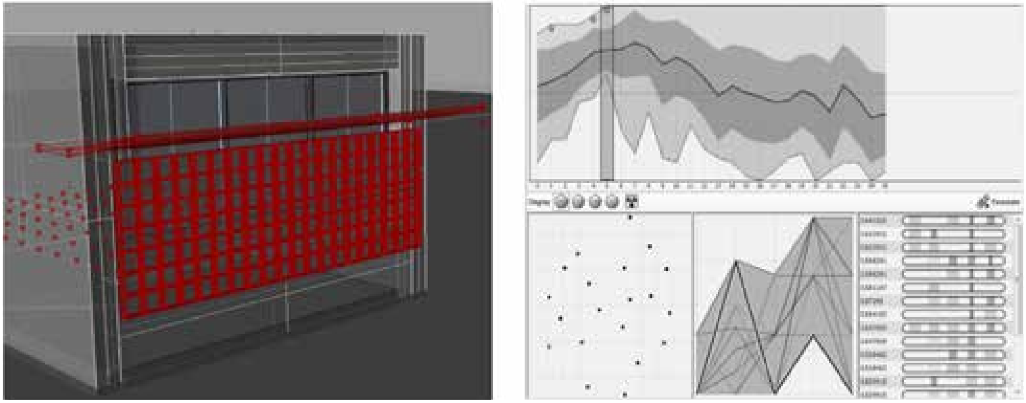


Figure 3
First case study after 26 generations, fittest design had 64% daylit area.

Table 4
Cases with highest performance for the first case study. It's noticeable the diversity in the solutions and the relatively small overlit area percentages.

81	93	92	89	95	86	91	94	85
83	92	-7	95	93	92	95	94	81
82	90	91	95	94	93	91	88	77
75	79	83	92	86	86	80	85	78
65	75	75	79	77	78	79	73	71
60	66	66	75	75	73	66	71	60
57	64	64	66	67	67	67	62	59
44	56	57	61	61	64	56	54	52
37	42	52	50	54	51	48	54	43
32	42	40	42	40	45	46	41	30
24	24	26	34	34	27	33	34	34
19	22	32	26	26	32	28	29	28
14	20	26	31	27	31	21	19	20

Screen configurations: 90%, 1:1, 40°
Light shelf configurations: Ext. 100 cm. 10°, 60 cm Int.

Daylit	64%
Overlit	0%
Partially Daylit	36%

93	95	95	96	96	95	96	95	91
92	95	96	95	96	95	97	95	93
84	88	94	96	93	92	94	94	82
83	80	93	93	94	93	88	93	83
71	80	87	89	-7	-7	-7	-7	76
72	78	81	84	83	88	82	77	75
60	68	68	76	69	72	68	75	63
52	57	60	59	63	65	57	55	52
46	48	58	58	53	54	53	49	45
29	42	38	41	47	44	40	48	33
20	30	29	27	34	35	37	34	35
17	18	26	31	32	29	21	28	25
17	17	14	19	24	27	26	25	21

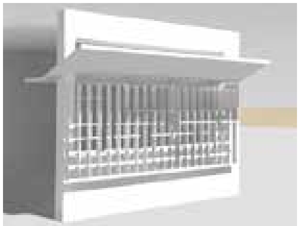
Screen configurations: 90%, 2:1, 50°
Light shelf configurations: Ext. 100 cm. 0°, 60 cm Int.

Daylit	62%
Overlit	3%
Partially Daylit	35%

94	97	97	97	97	-5	96	96	92
93	97	97	-5	97	-5	97	-5	95
92	92	92	97	95	95	96	93	89
86	90	94	93	95	92	94	85	86
84	83	90	92	-7	-7	-6	-6	86
76	80	83	83	82	82	82	75	74
63	71	68	78	75	74	74	75	64
56	60	63	68	69	66	60	63	59
41	55	56	57	58	57	56	53	51
32	40	39	42	46	50	48	48	38
29	27	31	32	32	36	41	34	35
19	17	27	30	33	32	32	31	28
8	21	20	24	25	30	28	24	22

Screen configurations: 90%, 4:1, 40°
Light shelf configurations: Ext. 100 cm. 0°, No Int.

Daylit	62%
Overlit	7%
Partially Daylit	31%



85	94	93	96	94	93	94	91	88
85	95	-10	-11	-10	-11	-10	-5	-10
82	87	91	95	96	94	94	93	86
78	86	88	92	91	93	93	77	77
62	70	75	77	84	89	80	83	69
62	74	74	72	77	74	75	70	64
65	67	59	72	70	60	71	64	57
46	56	57	61	59	60	54	59	55
46	51	55	58	57	56	56	59	44
38	44	42	42	47	43	48	42	43
28	24	35	38	36	39	38	42	31
20	27	31	34	29	38	33	28	23
17	23	26	26	28	28	27	20	19

Screen configurations: 80%, 1:1, 40°
Light shelf configurations: Ext. 120 cm. 20°, 60 cm Int.

Daylit	61%
Overlit	6%
Partially Daylit	33%

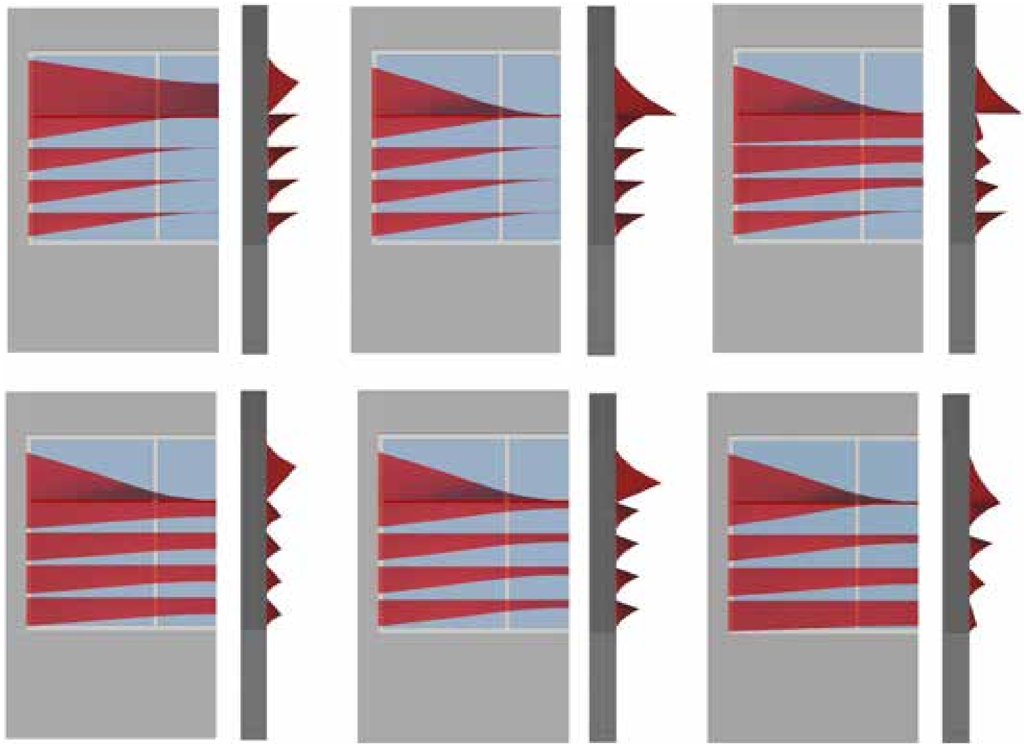


Figure 4
ifferent shapes and settings for the façade of the second case study.

surface is a free form inspired from nature and has been recently used in several architecture works.

The proposed system was applied to the South facade and was parametrically controlled to provide a wide range of options. Every louver had a median control point which represents the curve peak. This point has the ability to move in the vertical and horizontal direction to control the openness and closeness of that part as well as the amount of shading it provides. The transition of the rest curve points is, however, not unique; Instead it follows a *Gaussian* curve were transition is defined by a symmetrical sequence of values, with null extremes. Similarly, the curved light shelf in the upper part has a similar point that controls its extension and curvature. Sixteen positions are optional for each single part of the system and more than two millions different designs are obtainable. Such a huge pool of design choices highlights the necessity of using tools such as genetic algorithms for finding designs that can provide suitable performance (exploratory analysis). Figure 4 shows different shapes and settings for the façade.

Daylighting performance optimization results

The algorithm succeeded in providing several acceptable cases considering the fact that the designs were found to have a wide range of performance (oscillated from 56% high to as low as only 5%). It might be useful to use such a tool to limit the options in the beginning of the design phase. An optimal solution was obtained in the second generation and continues to be the fittest for the remaining

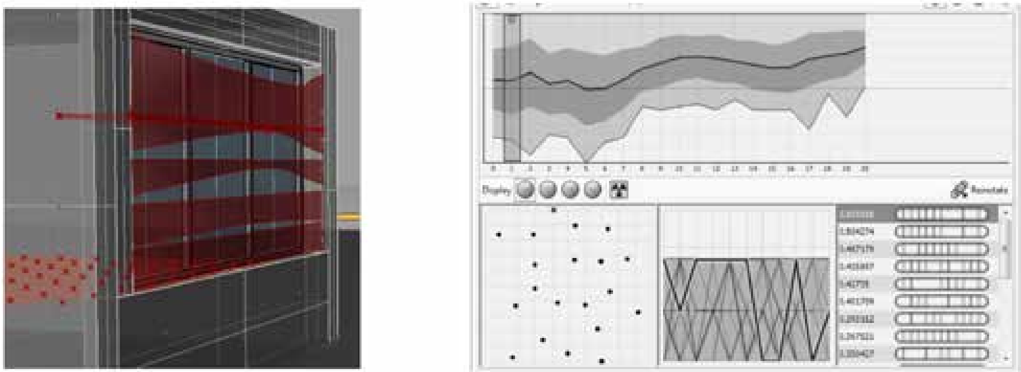


Figure 5
Second case study after 21 generations, fittest design had 56% daylit area.

twenty generations. The optimal solution had 56% daylit area. Results show that the algorithm wasn't able to conduct a real optimization, most likely because of the extremely wide solution space and the simple characteristic of the algorithm. Larger generations and more computing time (more generations) would have possibly reached better results. However, it's hard to judge the success of the algorithm without further optimizations. Figure 5 shows the optimization progress and Table 5 shows the best performing cases.

CONCLUSION

The two studied cases demonstrated the ability of the Genetic Algorithm in producing designs with acceptable daylight performance. However, the performance of the optimization tool was found to differ based on the complexity of the problem. In the first case, The GA reached a near optimum solution and succeeded in reaching solutions that have a significantly better performance compared to the base case. It's, therefore, recommended to use optimization tools and evolutionary solving methods in guided searches for optimal solution from various possible options.

In the second case, and because of the vast number of solutions, the algorithm seemed to settle with a local optimal. Although, it may be hard to judge the results unless more optimization trials with different setting are made, the algorithm was found to be a suitable exploratory method to limit the options when no previous experience is available. This is an exceptionally useful feature that enables the integration of performance analysis in earlier stages of design.

The proposed methodology can be adjusted to

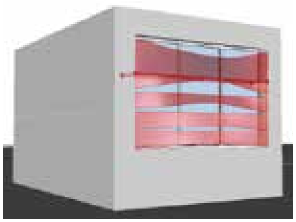
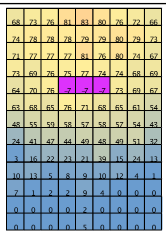
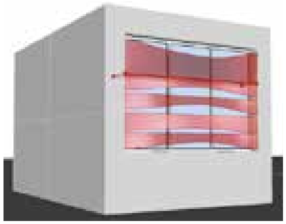
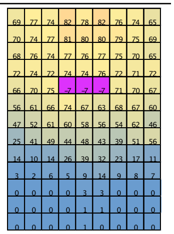
			
Daylit	56%	Daylit	53%
Overlit	2%	Overlit	3%
Partially Daylit	42%	Partially Daylit	44%

Table 5
Cases with highest performance for the second case study.

diverse contexts and objectives. Form generation and form finding using evolutionary solvers can open the door for more performative designs with unlimited creativity and minimum restrains. The proposed methodology can also aid architects in taking design decisions in the early design stages.

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Models of Computation: Form Studies

Algorithmic Form Generation for Crochet Technique

A study for decoding crocheted surface behaviour to explore variations

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Abstract. *In architecture use of generative computation suggests a possibility of rethinking the form finding process. In order to generate form, one method could be predefining first the production technique and constraining the form by the rules of it. In this study crochet-knitting technique is chosen as a production technique. To explore various forms developed through this technique; a computational model, which the behavior of crochet-knitted surface is embedded into, is developed. This paper explains the process of decoding the behavior of a crochet-knitted surface for a computational model in order to extract the crochet-knitting patterns of complex geometrical surfaces.*
Keywords. *Form generation; crochet technique; hyperbolic geometry; decoding rule*

INTRODUCTION

This research aims to understand the behavior of a crochet-knitted surface and decode its rule for a computational model so that it can be utilized in architectural design process. Use of generative computation suggests a possibility of rethinking the architectural design process. Such rethinking could lead to slightly different comprehension of the designers' decision making. In this study, the production technique is predefined (crochet-knitting) and the form generation is constrained by the rules of production technique. Through algorithmic process of crochet-knitting technique, various surfaces -which imply spatial and structural features- can be generated and automatized for physical production through a computational model. This computational model, which contains the knowledge of knitting surface behavior, facilities exploration of various forms developed through crochet-knitting technique. Once a form is developed through this computational model, the rule that is extracted from this computational model is generic and also used for physically knitting of it (Figure 1). This paper illustrates the first stage, which is concerned with the development of crochet-knitting computational model. Further research of this study will follow automatizing the physical production.

ALGORITHMIC THINKING IN KNITTING

Algorithm is a precise specification of a sequence of instructions to be carried out in order to solve a given problem (Rajaraman, 2003). Each instruction tells what task is to be performed. Algorithm serves as a codification of the problem through a series of finite, consistent, and rational steps. Although the sequence of an algorithm is simple, the outcome could still be very complex and unpredictable. Fol-

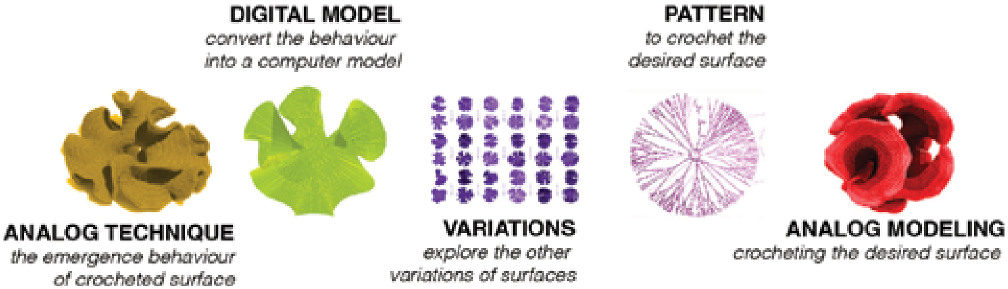

Figure 1
Process of the research aim

lowing some specific rules -or a sequence of instructions to do a job- is used in many fields. Knitting is one of the main algorithmic procedures utilized by humans till their early existence. The example below highlights the relation between knitting instructions and algorithmic thinking.

Example: Instruction to knit a sweater

Step1: Cast on 133 stiches

Step2: Repeat steps 3 and 4, 11 times

Step3: Knit 2, *Purl 1, Knit 1, Repeat from * to last stitch, Knit 1

Step4: Knit 1, *Purl 1, Knit 1, Repeat from * to End…Similar steps (Rajaraman, 2003)

By proper permutation and combination of this elementary set of actions (knitting, purling, casting stitches on or of needles), an infinite number of knitting patterns can be created. The algorithm, which is the rules for generating knitting patterns, can be also seen as a translator between human mind and computer. The power of computation, which involves vast quantities of calculations and recursions, can detect abilities that may have not ever occurred to the human mind. The computational model, which is based on knitting algorithm, expands the limits of human imagination.

The algorithm instruction given above example illustrates that knitting technique can be automated due to its algorithmic process. Knitting machine, which is invented by William Lee in 1589, uses almost the same principle with hand knitting [1]. It knits patterns with algorithmically defined needle movement. Today, the needle movements can be controlled by computers, but the mechanism of the knitting machines is not developed. If the mechanics of these knitting machines can be modified for certain behaviours, it would be possible to knit as a whole, those complex forms that explored through the computational model.

KNITTING TECHNIQUE

Knitting is a technique where one continuous line/thread composes not only Euclidian but also non-Euclidian surfaces with a very simple operation. As stitches are added, they push and pull on each other and create an emergent surface. The size of those stitches, and the number of their neighbours in the rows above and below, determines the shape of the work [2]. For knitting a desired surface, the mathematical concept of the surface needs to be converted into a pattern. This conversion requires a greater understanding of the behaviour of the knitted surface because one has to figure out where exactly to increase and decrease stitches so that the resulting surface as a whole is as close as possible to the desired surface. Each work can be quantified as its own pattern. Once knitting pattern is derived than it is generic and the same surface is created aside from the tension of the working yarn. Crochet as one of the knitting techniques is chosen for handmade experiments, since it is easier to compose complex surface. However the surface that is composed through knitting technique is looser than the crocheted surface, both techniques essentially create the same geometry.

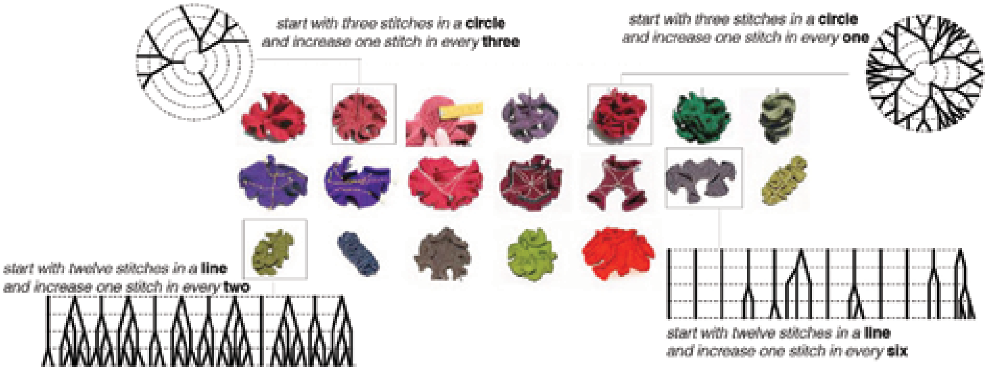

Figure 2
Hyperbolic crochet variations of Daina Taimina and its crochet patterns.

CROCHET GENERATES HYPERBOLIC GEOMETRIES

Hyperbolic geometry is a surface that has infinite number of lines that go through a point that is specified on the surface but never meet the line that is described on the surface previously [3]. When hyperbolic geometry was first discovered, mathematicians did not understand how it looks like. In 1997, Mathematician Daina Taimina did explain how hyperbolic geometries look like by using her crocheted and knitted surfaces. She found out that just by repeating a very simple operation, it is possible to knit variations of these complex mathematical geometries (Figure 2).

Daina Taimina has crocheted variations of hyperbolic geometries by starting from a row of fixed stitch number and then adding rows. The principle of generating hyperbolic surface is adding one extra stitch in every *n* stitches (David and Taimina 2001). The number of stitches increases per row and this arises negative local curvature. If *n* is smaller, more crochet stitches are added so that the concluded surface has a larger negative curvature. This curvature is constant if the process is repeated the same everywhere (Osinga and Krauskopf 2004). This fact demonstrates that the crochet technique promises to create complex surfaces even with a very simple, repeated operation.

DESCRIBING THE CROCHET SURFACE BEHAVIOUR

Every single decision of increasing or decreasing stitches affects the shape of a whole crocheted surface. While making decisions for each stitch, it is almost impossible to predict how the entire surface would be affected from this decision. It is because crochet a desired surface is mostly an intuitional act and it is not so easy to describe what makes a linear thread to create a 3D surface. This makes the behaviour of the crocheted surface emergent. An emergent behaviour or emergent property can appear when a number of simple entities operate in a system to form more complex behaviours together. The reason of emergent behaviour is usually the relation across different scales and there is often a top-down feedback in entire system. Such emergent behaviour cannot be modelled through a standard modelling software, since it should be embedded into the modelling tool. This requires the necessity to understand the behaviour of the stitches on the knitting surface. In order to find out the geometric logic of this emergent behaviour, another technique of constructing hyperbolic geometry is studied. This technique is called polyhedral model. Polyhedral model consists of equilateral triangles and creates a hyperbolic surface if each vertex on the surface belongs to seven equilateral triangles (David, Taimina

2001). Since these two techniques can compose the same hyperbolic surface, is there any connection between them?

As a result of exploring these two techniques, in both of them there is the same physical attraction that forces the whole surface into a hyperbolic form. In other words, the polyhedral model behaves almost the same as the crocheted surface. Each stitch in the crocheted surface behaves like one equilateral triangle in the polyhedral model. While in crocheted surface, each stitch pushes and pulls on each other and whole system creates an emergent 3D surface, in polyhedral model each edge of the equilateral triangles tries to stabilize itself in the same distance. This knowledge is the key argument that enables to perceive and geometrically describe the behaviour of the crocheted surface.

In order to establish the relationship between crocheted surface and polyhedral model, the crochet patterns that are extracted from polyhedral models are tested. In this research: instead of equilateral triangles; pentagons, hexagons and heptagons are chosen for computational and physical model generation. Because using these polygons generates similar smoothness that the crocheted surfaces have (Figure 3).

As shown in Figure 4, hexagonal pattern generates a flat surface. If pentagons and heptagons are also inserted, the system deforms itself into 3D surface.

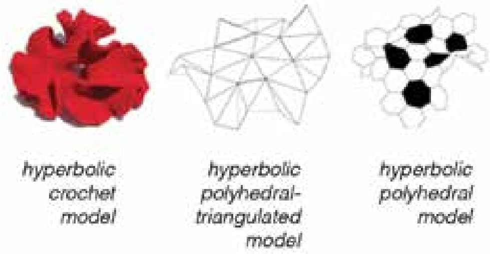

Figure 3
Crocheted, polyhedral models consist of triangles and polygons.

COMPUTER MODEL OF GENERATING SURFACE

The computational model (Figure 5) that simulates crochet technique is created through the polyhedral logic given above and is coded in *processing programming* language. Each pentagon, hexagon and heptagon is added one by one and attached to each other with at least two vertices of the previous polygon. The code defines vertices as well as the centre point of each polygon as a node and forces each node in order to be in the same distance with its neighbours. The form of the surface is governed by the position of these nodes, which provide an easy process for calculating the overall geometry. In *processing* code, each node as a particle is connected with its neighbouring nodes through springs. Therefore, the position of each node needs to be calculated until an equilibrium state was reached for the entire model while any node is added. During modelling, each node determines the emergent be-

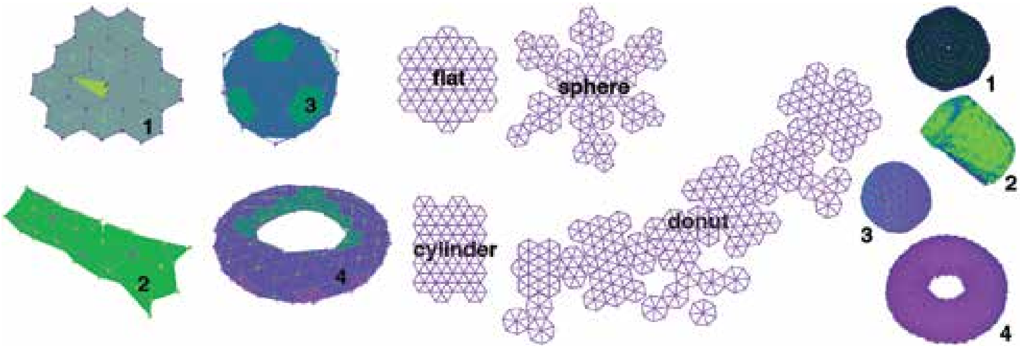

Figure 4
Extracting crochet rules from polyhedral model.

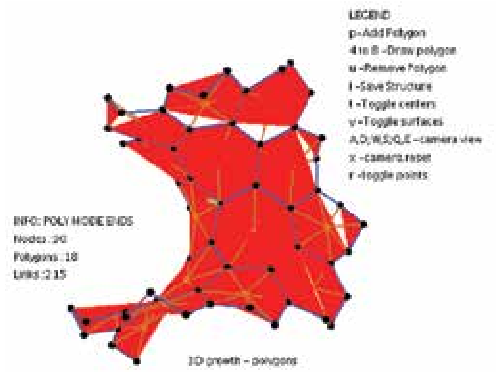

Figure 5
Print screen of the code interface written in processing programming language.

haviour by affecting on the overall shape. The process is iterative and it has a different approach than a standard computational modelling. It does not start with a pre-defined geometric surface, besides the generated geometric surface is unpredictable. The process of form generation is nonlinear and it enables negotiation between several nodes simultaneously. This negotiation between nodes generates the global form from the local conditions and decisions. The computational model does not have any material properties such as elasticity, etc. because the geometry of the concluded knitted surface is not affected by the property of the material. On the other hand the material affects the rigidity of the concluded form.

EXTRACTING THE KNITTING PATTERN

To generate the prototype, the code, which is written in the *processing programming* language, is used to create computational polyhedral model of the desired surface. The creation of the surface starts with the first polygon definition then the user controls the surface generation by deciding the position and the number of the edges of the next polygon. Once computational model is generated then it is printed as a flattened surface to build its physical paper model. The pattern of crochet prototype (the number and the order of the stitches for each row) is extracted by counting the number of triangles in each vertex on the paper model. This pattern that is the output of the computational model is used for crocheting the replica of desired (Figure 6).

REALIZATION OF A FULL SCALE PROTOTYPE

To scale the production of crocheted surface, the polyhedral model is also used. In polyhedral model if the number of equilateral triangles is increased, the scale of the whole crocheted surface becomes bigger. In order to increase the number of triangles, loop subdivision method (Figure 7), which is developed by Charles Loop, is applied. This method multiplies the triangles by adding new vertices in the middle of each edge [4]. This polyhedral model with more triangles –created through loop subdivi-

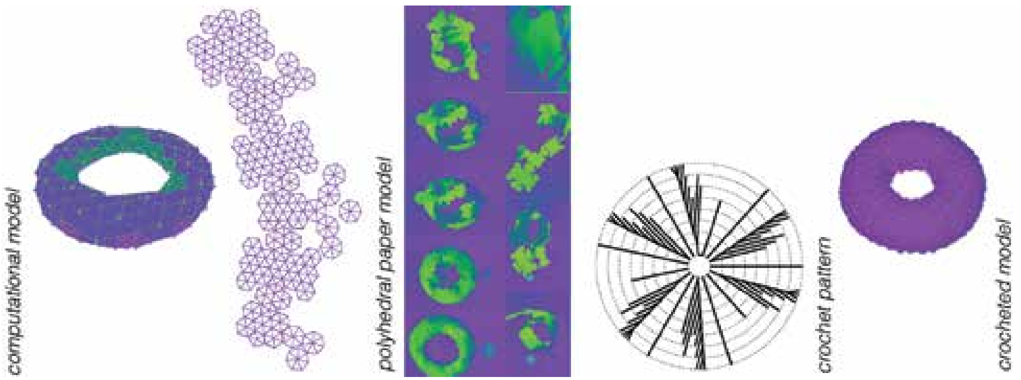

Figure 6
The whole process from digital model to analog crochet.

sion method- is used to extract the crochet pattern, which will make the crocheted geometry bigger.

CONCLUSION

This research demonstrates that extracting the crochet rules for each surface is possible through computational polyhedral model. The crochet technique is more promising than Taimina's crocheted models that are shown in Figure 2 in order to generate different variations of hyperbolic geometries. Using hyperbolic geometries in architecture have an important potential since they present an opportunity to achieve self-contained structures. But the conventional way of building them is expensive and it results in material wastage because of complex custom-made casting. In this context, crochet technique could provide building hyperbolic structures by eliminating the need for complex casting. Moreover, the crochet rules that are extracted from computational polyhedral model can also be used as *generator code* during the further research on digital fabrication of these complex crocheted surfaces (Figure 8).

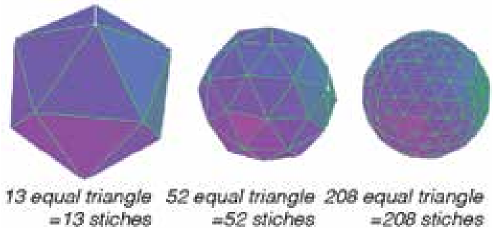

Figure 7
Loop subdivision methods.

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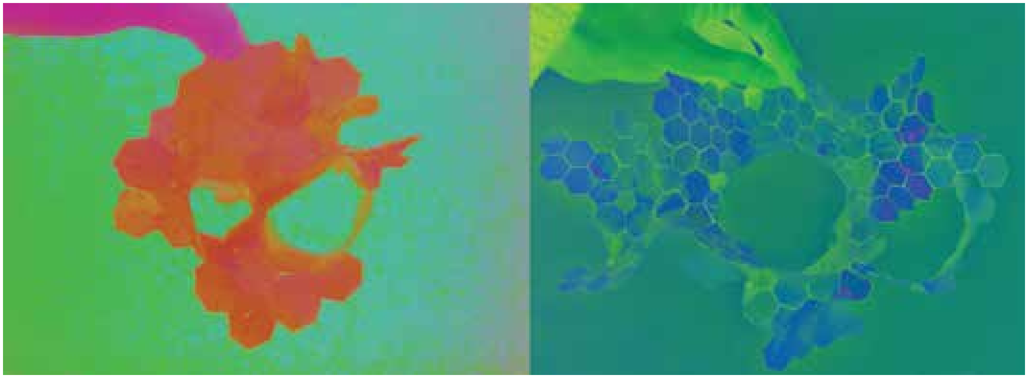

Figure 8
The polyhedral models that are chosen for prototyping.

3D Regular Expressions - Searching Shapes IN Meshes

The development of an algorithm to identify recurring geometries

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Abstract. *We have grown accustomed to performing elaborate queries on textual data, e.g. via online search engines, file system managers and word processors. In the past decade, retrieval methods that also work on non-textual data have become mainstream (e.g. face recognition software). Sadly, these developments have so far not caught on for data mining within geometrical data, e.g. 3D meshes generated in the course of architectural work. Specifically during data exchange, such a search functionality would be handy, as it often happens that geometry is exported but object identity is lost - think, for example, of generative geometry or exported BIM data. In this paper, we present an example of such a search functionality, based on angular search. Our method is inspired by regular expressions, a string matching technique commonly employed for matching substrings.*
Keywords. *Shape retrieval; angular search; sub-mesh; regular expressions.*

NAÏVE IDEA

Instead of an introduction, let us jump directly to the idea behind the search algorithm and see how it can be applied within the architectural workflow: Assume that we have imported a large mesh into a modeling environment, in which all information but the list of vertices and faces is lost. Such a situation can occur during data exchange, entailing two **major problems**:

1. there is *no object identity*, i.e. we have to manually select vertices and faces belonging to an object in order to work with it. This can be a challenging task, though, as geometry might overlap (see Figure 1a).
2. In cases where there is *more than one instance of the same geometry*, a manual approach is highly tedious. Furthermore, the modeling environment has to load identical geometry multiple times into memory, which may prohibit working smoothly with the mesh for lack of performance. What is needed is an approach that can replace instances of the same geometry by a reference to a single one.

Our **contribution** concentrates on solving the mentioned problems and additionally brings forward a "search and replace" functionality for 3D meshes. In more detail, we present an algorithm that

- can *find shapes IN meshes (i.e. sub-meshes)*, given a search pattern in the way of a set of paths (which we interpret as succession of angles);
- can *restore object identity,* thus making it possible to work with a possibly inaccessible collection of vertices and faces;

- can *replace* found geometry *by a reference to a single geometry container;*
- can *replace* found geometry *by a different geometry.*

Figure 1 gives two results obtained with the approach: In Figure 1a, object identity was restored from a previously inaccessible polygon soup. In Figure 2b, we have searched for the given outline and replaced each occurrence by a different geometry. The latter takes 19s on a 2.4GHz single-core processor (C++ implementation, mesh containing 12064 vertices), which is moderately fast. The pattern is given as own mesh, which is automatically compiled into a search description which our algorithm needs.

In the coming sections, we will describe exactly how the search is done and how the mentioned compilation proceeds (see "Background" and "Elaboration"). We further provide details on the studies conducted (see "Studies"), which have served as test-bed and ground for discussion concerning the future development of the tool. Before concluding, we also deliver details on the two implementations existing so far (see "Implementation").

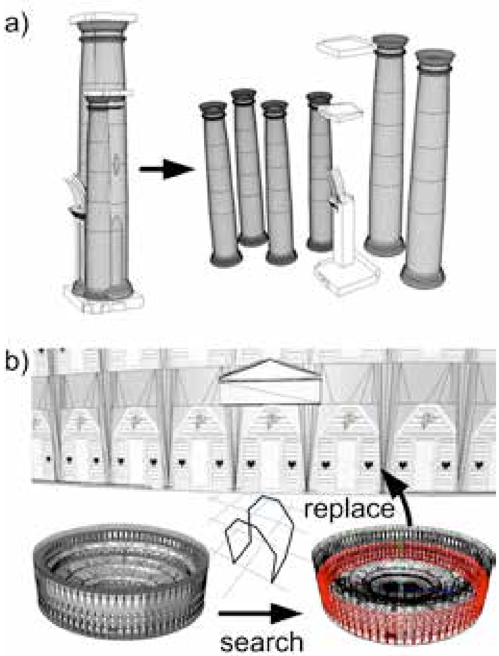

Figure 1
Searching and replacing in meshes. (a) Restoring object identity from a polygon soup. (b) Searching and replacing geometry within a mesh.

BACKGROUND

The approach is based on two underlying methods, *regular expressions* and *angular search*. Therefore, we first take a quick look at both, before elaborating the details of the presented method.

Regular expressions

A regular expression (regex) is a textual search technique that specifies a searched string by supplying a grammar of characters to match. We do not intend to give an elaborate introduction into this topic here, as this information is widely available and considered a standard technique in computer science. We instead forward the interested reader to (Forta 2004) and focus further explanations on the constructs that the search algorithm uses (also see Table 1):

- A string is a sequence of characters, a mesh a set of vertices connected by edges. We search for paths within that mesh, taking the sequence of angles between each pair of edges on that path as criterium.
- Meshes can be tesselated, meaning that each edge can be subdivided. The intermediate points do not contain significant information when we consider only angles as matching criterion. We thus adopt the regex repetition, in order to "jump over" points that lie in the same direction as previously encountered ones.
- The specified angular paths can self-intersect. In order to check that the same point is reached, we adopt the notion of back-references, i.e. the storage of a point that was reached so far for later equality comparison.

Throughout the paper, we will use a couple of termini found in regular expressions. To begin with, we use the word *automaton* to signify a list of matching criteria (*transitions*) that are evaluated sequentially. As example, take the following regular expression "ab". This specifies two transitions "a" and

Table 1
Regular expressions versus 3D regular expression.

Regex construct	matches e.g.	becomes in 3D regex algorithm
character sequence, e.g. abc	abc	angle sequence, e.g. 90° 10°
repetition (one or more times), e.g. a+	a, aa, aaa	match vertices in same direction
backreferences, e.g. (a|b)\1	aa,bb	match previously encountered point

Table 2
Transition types used in the automaton.

Transition	long name	meaning
FAIL	Failure Transition	ends execution, reporting failure
MATCH	Match Transition	ends execution, reporting a submesh
ANG	Angle Transition	at current point, find edge pairs having angle
CLO	Closure	find points in the same direction
BOR	Begin of Regex Group	begins a new regex group (for backreferencing)
EOR	End of Regex Group	ends a regex group, storing the curring point
REF	Backreference	references a previously matched point or point at a certain percentage of a visited edge
BAT	Begin-At	begins matching at a previously matched point

"b" which are put into a list ("a" "b"). Implicitly, two more transitions are added to the head and the tail of the list, namely MATCH and FAIL. Both signify a stop condition - in the first case, the algorithm has found the supplied string, in the second case, the algorithm has failed. The list of transitions thus becomes (FAIL, "a", "b", MATCH). An automaton has a *transition pointer*, placed initially on the *second* item of the list ("a"). Each transition type has its own way of matching. In the simple case mentioned, we have a character transition, which compares the current character in the string to the one specified. If both are equal, the transition pointer is advanced ("b"). This process is repeated until we finally encounter MATCH. In the case that the criteria specified in the current transition are not satisfied, an error flag is raised and the transition pointer is set to the preceding transition.

Angular search

Angular search is concerned with finding a sequence of angles in a given geometry. Examples of such algorithms are to be found in the automotive industry, in the form of a search tool for mechanical parts in a large CAD database (Berchtold and Kriegel 2004). However, in the concrete case mentioned, only section plans were taken into account, and the whole algorithm was limited to 2D retrieval. In contrast, our algorithm searches in 2D or 3D and additionally takes proportions into account (i.e. surplus to the angular search). Examples of other shape retrieval techniques, which use statistical data instead of angles, are the ShapeSifter tool that is based upon features such as surface area, volume etc. (Sung, Rea, Corney, Clark and Pritchard 2002) and the Princeton Shape Search Engine which can compare sketches to sections (Funkhouser, Min and Kazhdan 2003).

ELABORATION

Our search technique describes an angular path the transition types given in Table 2. The most important one is the angle transition (ANG), which tries to find an edge pairs having a given angle, extending from the current point. This is usually followed by a closure transition (CLO), which jumps over any intermediate points lying at the same angle (as mentioned, these do not contain significant information). As further transition types, we have begin and end of a regular expression group (BOR, EOR), backreference (REF) and begin-at (BAT). These are described in due course, using examples to help understanding. As in regular expressions, we also have FAIL and MATCH; the latter reports the points encountered during the whole matching process, i.e. the sub-mesh found.

We will now walk through the different possibilities for implementing a regular expression au-

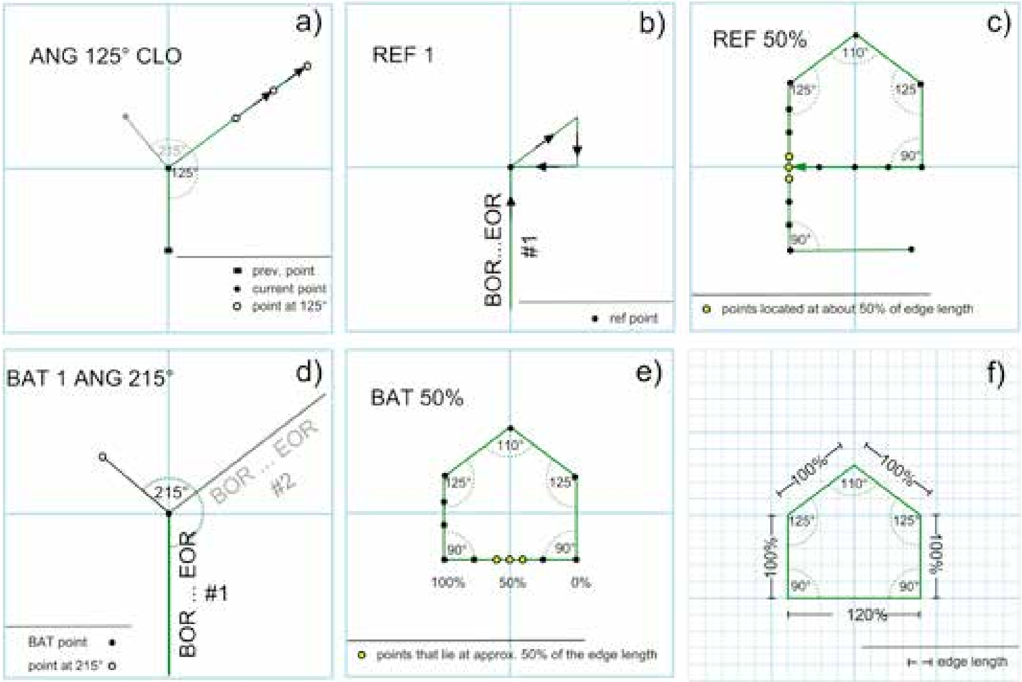

Figure 2
Transitions. (a) Angle and closure (b) backreference to point and (c) to edge, (d) branching at a point using the Begin-At transition, (e) branching 50% of an edge, counting from its start. (f) Relative edge lengths used to introduce proportions.

tomaton, starting with the 2D case and extending this to 3D. We also give details on the used compiler, which converts a search pattern (a mesh consisting of paths) into an automaton.

The 2D regex automaton

Two different modes are considered in the 2D case: If this is the first ANG to be matched, then an *inner angle* (0...360°) between edge pairs situated at the current point is found. In all other cases, the edge last taken is already fixed: The automaton then searches for a next edge at the correct angle with reference to the previous one. Depending on required strictness, angles are compared using a tolerance interval. The same applies to the matching of intermediate points. In the case no suitable angle is found, the algorithm gets to the previous transition and tries the next edge pair.

Figure 2 brings examples of such a 2D search: In Figure 2a, we search for an angle of 125 degrees formed by the current point (shown in the center), the previous point (shown as a tiny rectangle) and a possible next point (shown as circle). Two cases are distinguished: (Case 1) If there is yet no previous point (because we have just started), we try the combination of all neighbor points *twice* (neighbor 1 - current point - neighbor 2; neighbor 2 - current point - neighbor 1), since that establishes the marching order of the algorithm. (Case 2) In case that there is a previous point, as shown, the algorithm tries to continue along a non-visited neighbor which has the correct inner angle. Regardless of which of both cases the algorithm has dealt with, the marching direction has been fixed (shown by an arrow). The next transition, a closure, consumes all points of the mesh lying in that direction, which allows us to skip past points that contain no significant angular information.

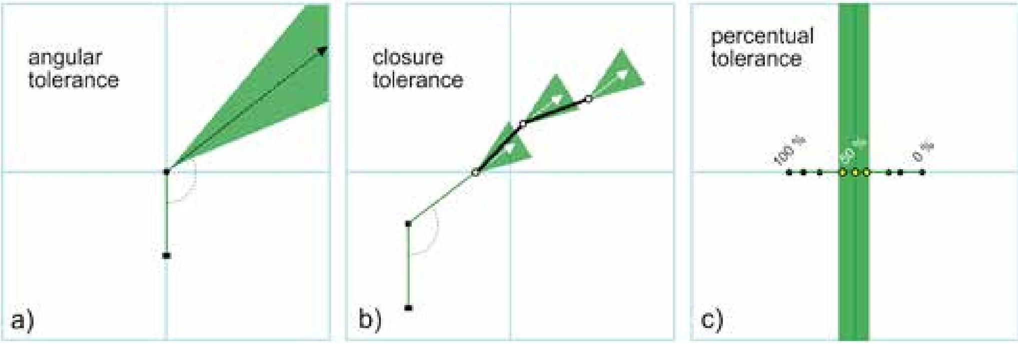

Figure 3
Tolerance values. (a) Angular tolerance at points, (b) closure tolerance for marching forward, (c) percentual tolerance for matching edges.

In Figure 2b, a backreference (REF) is shown where the path self-intersects. Two steps are needed to make such checks for self-intersection possible: The preceding transitions are enclosed in a begin-of-regex (BOR) and end-of-regex (EOR) group, in this case: the first regex group (#1). Internally, the automaton stores all points encountered when matching that group. The backreference REF 1 checks whether the current point corresponds to the last point encountered in regex group #1.

A variation of a backreference is given in Figure 2c: Here, REF 50% checks whether the current point corresponds to one of the matched points of a regex group situated within a certain percentage of the edge length. Thus, this specific flavor of REF checks for self-intersections with an edge.

Figure 2d shows a fork: The regex has so far matched regex group #1, arriving at the point shown in the center. It is now possible to begin at that point when matching, using the begin-at transition at group 1 (BAT 1). In the example shown, one might BAT 1 for matching the right path, before executing BAT 1 to find the left path.

One may also begin matching at a certain percentage of a previously encountered edge, as shown in Figure 2e: From the matched points of the given regex group, the algorithm selects the ones lying within a tolerance interval around the given percentage (BAT 50%) and tries to match onward from these.

Introducing proportions

So far, the regex algorithm is length-invariant, as it considers only angles. However, *relative length* does make a difference when looking at *proportions*: A square is not the same as a rectangle, for example. Thus, we introduce length as shown in Figure 2f: Initially, we memorize edge lengths relative to the length first edge within the search pattern (*reference length*). During matching, we can reject points if they do not lie at a certain distance of an edge start, in the following manner: The edge start is given as an ANG transition, the edge itself is matched via a following CLO. The next ANG represents the edge end (and, at the same time, the start of a new edge). When trying to match the latter angle, one would usually start at the last point matched by CLO and then go back point by point until we have either found the angle or there are none left. However, because the relative edge length is known, we can consider only points established by CLO that are situated at a certain distance of the edge length (expressed in percent of the *reference length*). This minor modification is all that is needed to include proportions.

Tolerance intervals

A point yet unaccounted for are the tolerance values which govern the strictness of the search algorithm. We have three such intervals, as given in Figure 3:

- Angular tolerance (Figure 3a) defines what deviations from a prescribed angle is acceptable.

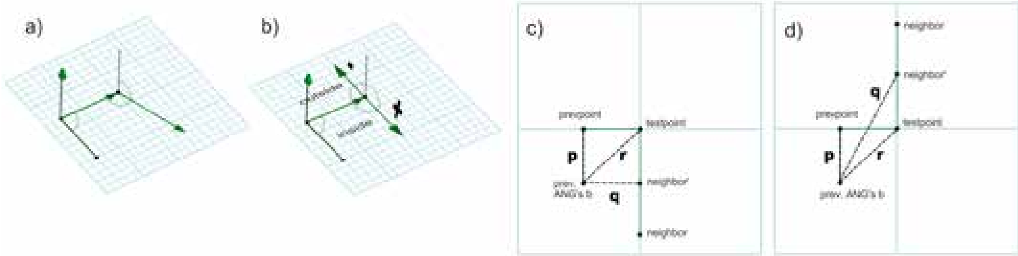

Figure 4
3D regex. We need an additional angle at each next point, (a) the angle between the previous normal and the next leg. (b) There is an ambiguity for successive 90° angles. Through comparison of lengths, we can find out whether we have an (c) inside or (d) outside winding.

- Closure tolerance (Figure 3b) specifies what deviations from the marching direction are to be accepted.
- Percentual tolerance (Figure 3c) states the interval around a percentage of an edge's length.

These three values are specified globally, for the time being. However, results obtained with the help of some basic test cases (see "Studies") show that this is a possible weakness of our algorithm, as we cannot easily adapt to sub-meshes that contain parts which require a more fine-grained, localized notion of tolerance. Thus, this part is likely to be extended in future implementations.

The 3D regex automaton

For the 3D case, the 2D regex algorithm is extended. In order to fix a next edge e_{i+1}, we need to take the last two edges e_i and e_{i-1} into account (refer to Figure 4a): The cross product e_i x e_{i-1} gives the normal vector n of the plane in which the last two edges lie. A suitable next edge is one that (1.) has the correct angle between e_i and e_{i+1} (same as in the 2D case) and additionally (2.) has the correct angle between n and e_{i+1}. Because of this, we need at least four points in the mesh to be searched.

An ambiguity arises for cases in which there is an ANG 90° following an ANG 90° (see Figure 4b), since it is not clear whether to march left ("outside") or right ("inside"). This case can be resolved through projection: Let (prev. ANG's b, prevpoint, testpoint, neighbor) be successive points, neighbor being the candidate for marching onward. Then, we have to fix three lengths p, q and r, as follows (refer to Figures 4c and d): p is the length (prev. ANG's b, prevpoint). An intermediate point neighbor' is a point situated at length p on the edge (testpoint, neighbor). The distance (prev. ANG's b, neighbor') is defined to be q. r is the length (prev. ANG's b, testpoint). If q is smaller than or equal to r, we can conclude that we have an "inside" winding (Figure 4c). In all other cases, we have an "outside" winding (Figure 4d). The winding criterion is added to the transition specification and compared at runtime with the mesh, for cases in which successions of 90° angles are present.

The regex compiler

The regular expression description is translated automatically from a search pattern made of paths (ordered edges) into a regex automaton. Briefly outlining the algorithm, we sequentially translate each edge pair into an ANG CLO (first pass). In that process, we ignore co-linear edges. However, these are needed later for checking intersections (second pass): (a) In case the end vertex of the forward edge was already visited, we generate a REF after ANG CLO. There are two distinct cases: If the visited vertex was co-linear (i.e. it was ignored during the first pass), we generate an edge reference (REF %). In all other cases, we surround the edge that leads to the point with BOR..EOR and generate a backreference to that regex group (REF #). (b) In case the start vertex of the forward edge was visited, we generate a BAT before ANG CLO in the previous fashion (co-linear: BAT %, else BOR…EOR BAT #).

STUDIES

Under this section, we examine the studies conducted with the regex algorithm in some detail. In

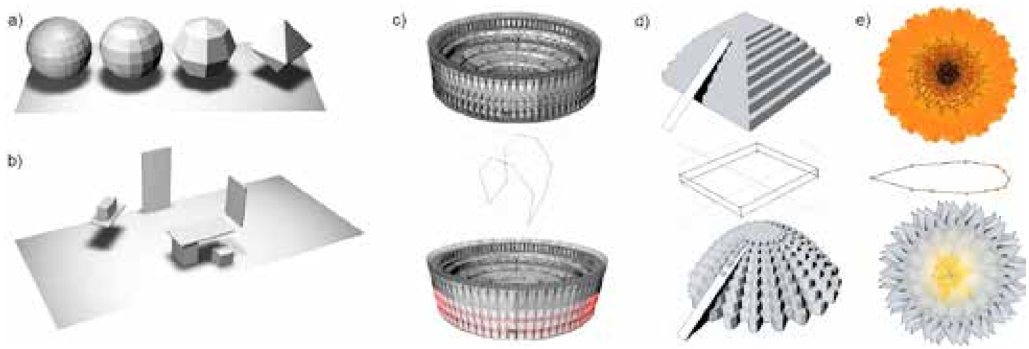

Figure 5
Basic Test Cases. (a) Sphere Matching (b) Proportion Check. Replacement of (c) Openings (d) Pyramid steps (e) Leafs.

all cases, we have applied a single regex pattern (acting as input) to a scene (also an input), producing an output in the form of a set of selected vertices and edges of the found sub-meshes. During evaluation, the number and type of matched sub-meshes (not all were "correct" in a visual sense, even though the angles and proportions matched) were compared to the type of regex used (ranging from "closely resembling" the searched sub-mesh to more perturbed versions). In a post-step, the replacement algorithm has been used on the selected point- and edge-sets or their connected components, typically placing and orienting an object such that it fit into the resulting bounding box. The latter is quite trivial to extend to arbitrary geometry that would be ill-suited for bounding-box placement, using specific rules stated in a scripted program of the modeling platform.

Basic test cases

During the development of the approach, we have used a set of basic test cases for assessing the algorithm:

- In the simplest case, we have looked at a set of spheres (Figure 5a) with increasing tesselation (4, 8, 16, 24 vertices as base). As result, we could show that a regex of k ANG transitions can only find objects with tesselation greater or equal to k (a 8-ANG regex will find the 8-, 16- and 24-sphere but not the 4-sphere).
- Proportions were tested on a scene resembling a room, simplified as cubes of different sizes (Figure 5b). We were able to find different geometries based on their proportions, however, it must be mentioned that we also had counterintuitive cases where geometry is so proportionally close that one regex intended for a specific type of furniture also returned a different geometry (not a false positive in the classical sense, though). We have furthermore perturbed the regex pattern, and checked that angular precision can comfortably cope with such errors.
- We tested the 3D "search and replace" algorithm using the colosseum mesh shown in Figure 5c. For every instance of the matched search pattern (shown red in the lower part of Figure 5c), we used the bounding box to locate the replacement. The orientation (heading, pitch, roll) of the replacement was concluded from the found points in comparison with the search pattern. Further tests for "search and replace" were also conducted with a pyramid (Figure 5d) and a gerbera, which was turned into a lily by replacing each leaf (Figure 5e).

Reconstruction of destroyed synagogues

We are currently testing the 3D regex algorithm on large-scale models in the context of virtual reconstruction of destroyed synagogues, mainly stemming of the period 1890-1910 (see Figure 6). Though hundreds of synagogues were in this era

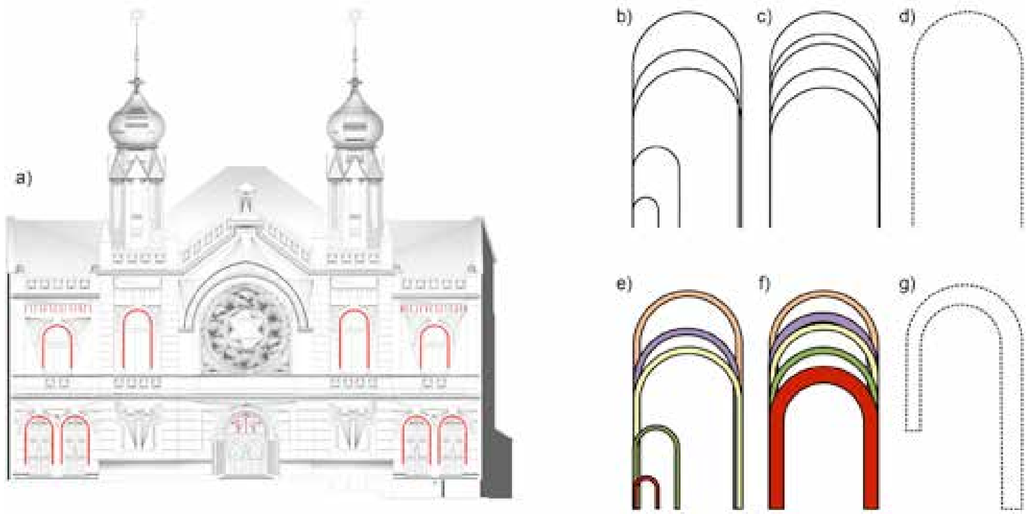

Figure 6
Matching "windows" in the synagogue case study. (a) Overview of matches, (b) arc - real size, (c) proportional size, (d) non-proportional size, (e) connected arc - real size, (f) proportional size, (g) non-proportional size.

built all over Europe, a significant portion has been destroyed in 1938. The option of re-erecting these sacral buildings is not on the agenda, particularly due to a missing usership locally. By way of a virtual reconstruction a certain degree of commemoration is facilitated. However, issues of incompleteness and missing bits and pieces of information play a central role in the process of reconstruction.

The collection of already realized 3D models serves as a knowledge base for ongoing reconstruction activities. However, the secure detection of already existing modeled elements - aiming at "re-use" - is cumbersome. First of all a subset of suitable entities has to be identified and eventual adaptation of the existing modeling properties might be considered. Instead of a laborious manual search through individual models, the goal is to be pointed in a straight-forward and structured way to (similar) building elements in the whole model collection. The 3D-model itself can be regarded as a structured database. Extracting information from a large set of models would enhance the orderly subsequent re-use of already modeled geometries. Any further building models added to the collection would presumably donate to the range of so far not recorded geometries.

To which kind of geometrical representations would this predominantly apply? In the past years the following sets of entities are for the building type "synagogue" of repetitive nature: furniture, bima and torah ark, ornaments, doors and windows, banisters, columns and ceiling beams, tower and dome elements. For our study, we have taken a first step in matching repetitive geometry, in the form of doors and windows (which we model as arcs, see Figure 6 for an overview), ornaments (Figure 7a), columns (Figure 7b) and ornamented windows (Figure 7c). We are far from finished with that undertaking, but the first results are already quite promising with respect to insights that would occur in a "real" project situation where geometry is to be searched.

To begin with, the mesh we are trying to search in can be considered a pathological case: Albeit being seemingly well-structured (see Figure 8a), a closer look reveals that it is composed of a multitude of overlapping components with little or no semantic interconnectedness. In the example in Figure 8b, we can see a door that is formed by a wall in the background (which is shared with another door to the left), a single arc in the foreground, and several ar-

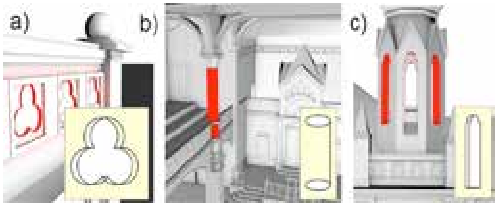

Figure 7
(a) Ornaments, (b) columns, (c) ornamented arcs.

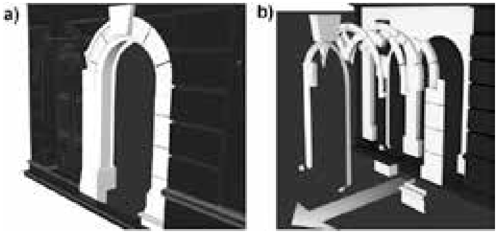

Figure 8
(a) Pathological door made of (b) arbitrary sub-meshes.

bitrarily connected arcs in the middle. Matching has proceeded only in the foreground arc, since that is at least connected. The truth is that, however, a designer would not know why the regex cannot match the whole door shown. What would be needed is an algorithm that can combine overlapping geometry in order to facilitate a "what you see is what you match"-sort of approach, which we have still not produced (future work).

Furthermore, there is a subtle influence by the regex chosen for arcs. Figures 6b and 6e show the real sizes of arcs that are matchable in the mesh. However, as the regex is size invariant, it actually "sees" only relative proportions as depicted in Figures 6c and 6f. Even if we increase percentual tolerance, we still get false positives, such as those above the main entrance (see Figure 6a). Optionally comparing the actual size of the pattern to the found instance may solve the problem, but this is again to be done as future work.

Choosing a regex without proportions reveals that the arcs all have the same radius (see Figures 6d and 6g). However, this is a bad choice, since that would also match every half-circle (height of the lower part close to zero). Without proportions, the situation is even worse in connected search patterns (Figure 6g), since we could get a deformed match which is hardly what we wanted in the first place. There is no way to circumvent this problem - matching without proportions just produces bad results (or, more precisely, results which are correct from an angular view but counterintuitive to us).

IMPLEMENTATION

At the moment, we have two different implementations: A plugin for the Maxon™ Cinema4D® modeling environment (written in C++), and a more academical implementation utilizing the NetLogo programming language. The first one was written in 2002 as part of the diploma thesis of the first author; the second one is a vanilla implementation that seeks to faithfully implement what was written in the thesis, in order to have some degree of quality control for this paper. NetLogo is rather slow with regards to performance, but its visualization capabilities and functional programming language make it an ideal test-bed for exploring further extensions of the approach.

Coming to performance, we disregard the NetLogo implementation (which is rather slow because of running on a Java Virtual Machine with added NetLogo stack on top). The C++ implementation is better - at average, 650 vertices per second per core (2.4 GHz 32-bit processor), although this largely depends on the mesh structure (good tesselation, connectivity/density), precision settings (more tolerance means more possibilities are tried, which slows down the algorithm) and the use of proportions (not using them generates more possibilities, again slowing down the program). For example, in the synagogue use case described earlier, the algorithm would find occurrences of the simple arc show under Figure 6c in either 6min 30s when the precision values were very strict (regex exactly resembling the sub-mesh, all precisions set to 1) or 1h 40min for a very loose setting (regex approximating the sub-mesh, angular and closure precision 30, percentual tolerance 10). This boils down to a performance of either 1500 (strict case) or 100 vertices (loose case) per second per core, with raises a variety of questions and analysis tasks for future work.

In that context, we also wish to note also that the overall efficiency is highly coupled to the search pattern (and thus: the compiler) used; a regex that discriminates early (i.e. sharp angles first, before coming to rounded forms) has a far better performance than one that considers discriminating factors as last step. Devising a better regex compiler and searching in an optimized mesh (overlapping edges and points merged) are clearly on our agenda. Also, future versions of the approach might lead away from the idea matching linearly in an automaton but recursively in the supplied search pattern (i.e. without compilation, but still utilizing the presented concepts).

CONCLUSION AND OUTLOOK

We have presented an algorithm that can search in meshes that have lost all information but their vertices and faces, based on regular expressions and angular search. The benefits of this are threefold: (1.) We can restore object identity, (2.) we can replace multiple instances of the found geometry by a reference to a single geometry container and (3.) we can replace found geometry by an alternative one.

Two case studies frame the presented approach: The "basic test cases", which we applied during development, and the ongoing "synagogue" test cases, which use a collection of models exported from CAD. As discussed, the first results with the latter domain have shown that the complexities associated with "real" data are not to be underestimated: The data is both huge (typically 350K vertices, 450K polygons) and of bad quality (overlapping geometry, unintelligible polygon groups forming connected components, bad tesselation). On top of this, the expectation regarding the growth of the model collection in the next coming years is expected to be substantial.

A meta-search will therefore become of even more importance, connected with a pre-step for automated simplification and cleaning of the mesh which lies on our future agenda. Also, building a library of patterns used for matching as well as a taxonomy that connects these would seem a useful extension that is yet too early to undertake, as we have to fix the foundations first. Other tasks that we would like to look into in the future are: data extraction from laser scan data and 3D fractal analysis of architecture based on "finding sub-meshes within sub-meshes".

ACKNOWLEDGEMENTS

This work is based on a diploma thesis (Wurzer, 2004) supervised by Katja Bühler (Vienna UT and VRVis Forschungs GmbH), Peter Ferschin and M. Eduard Gröller (Vienna UT). The synagogue model base is a results of a continuing effort in virtual reconstruction by Bob Martens (Vienna UT), Herbert Peter (Academy of Fine Arts Vienna), among many others participating in that effort.

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A Computational Method for Integrating Parametric Origami Design and Acoustic Engineering

An application to a concert hall design

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Abstract. *This paper proposes a computational form-finding method for integrating parametric origami design and acoustic engineering to find the best geometric form of a concert hall. The paper describes an application of this method to a concert hall design project in Japan. The method consists of three interactive subprograms: a parametric origami program, an acoustic simulation program, and an optimization program. The advantages of the proposed method are as follows. First, it is easy to visualize engineering results obtained from the acoustic simulation program. Second, it can deal with acoustic parameters as one of the primary design materials as well as origami parameters and design intentions. Third, it provides a final optimized geometric form satisfying both architectural design and acoustic conditions. The method is valuable for generating new possibilities of architectural form by shifting from a traditional form-making process to a form-finding process.*
Keywords. *Interactive design method; parametric origami; acoustic simulation; optimization; quadrat count method.*

INTRODUCTION

Design for a concert hall includes acoustic engineering and architectural design (i.e. aesthetically pleasing design that satisfies complex architectural conditions, such as concert activities, building regulations, structure, construction processes, budgets and so forth). Usually, computation is often used for generating all possible geometries fulfilling those various architectural constraints. However, the most difficult part of design processes is to choose the best geometric form among the resulting various alternatives.

This paper proposes a computational method for integrating parametric origami design and acoustic engineering to find the best geometric form of a concert hall. First, we discuss the limitations of conventional collaborations between architects and acoustical engineers. Second, to overcome these limitations, we develop an interactive design method and show its application to a concert hall design project in Japan (the hall will be completed in 2014). The design method consists of three interactive subprograms: a parametric origami program, an acoustic simulation program, and an optimization program. Finally, we describe the advantages of the proposed method, including the ease with

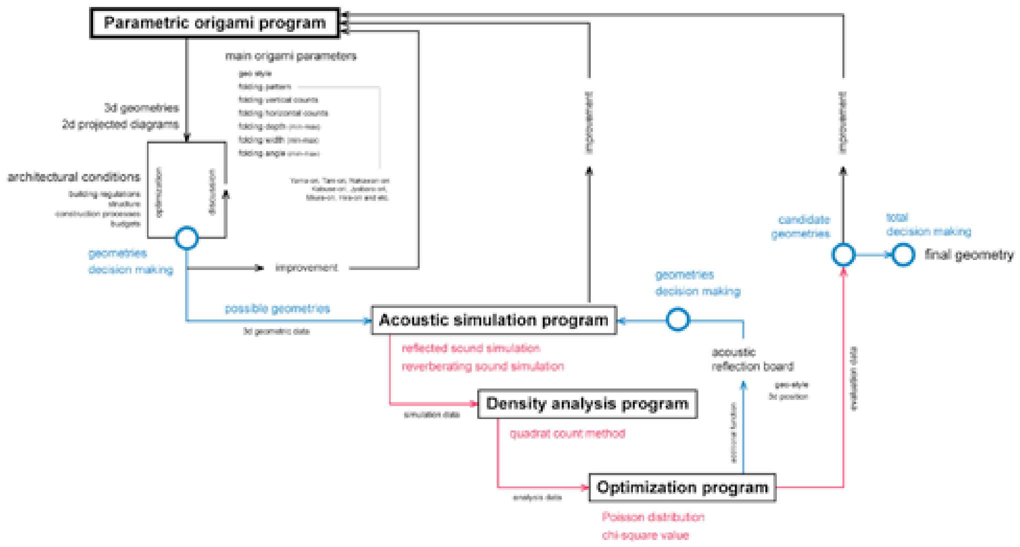


Figure 1
A diagram of the interactive design method.

which it visualizes engineering results obtained from the acoustic simulation program, and a final optimized geometric forms it provides to satisfy both architectural design and acoustic conditions. Because the method efficiently manages fundamental factors underlying architectural forms, it can provide a design framework in which architectural design and acoustic engineering are integrated.

THEORETICAL BACKGROUND

In the design process for a concert hall, architects collaborate with acoustical engineers. First, architects develop a geometric form and then acoustical engineers analyze the acoustic efficiency of the proposed form using their simulation program. However, there are relatively few exchanges between them. As a result, in the conventional method architectural optimization and acoustical optimization tend to be rather independent operations, and they are not always coordinated. For instance, acoustic optimization does not always take into account complex architectural conditions or the architects' design intentions, whereas architects do not always utilize informative data provided by the acoustical engineers. To bridge this gap, we propose a computational design method for integrating architectural design factors and acoustical engineering factors.

In addition, we want to develop an objective method in which acoustic data derived from a simulation process are efficiently utilized. In this connection, Leach (2009) mentioned as follows: "Within contemporary architectural design, a significant shift in emphasis can be detected – move away from an architecture based on purely visual concerns towards an architecture justified by its performance. Structural, constructional, economic, environmental and other parameters that were once secondary concerns have become primary – are now being embraced as positive inputs within the design process from the outset". Our proposed interactive design method can deal with acoustic parameters as one of the primary design materials as well as origami parameters and design intentions (Figure 1).

With the recent improvement of computer performance, simulation technology has improved significantly. As a result, it has become easy to visualize the state of the acoustic parameters. What makes our method intriguing is that those parameters can

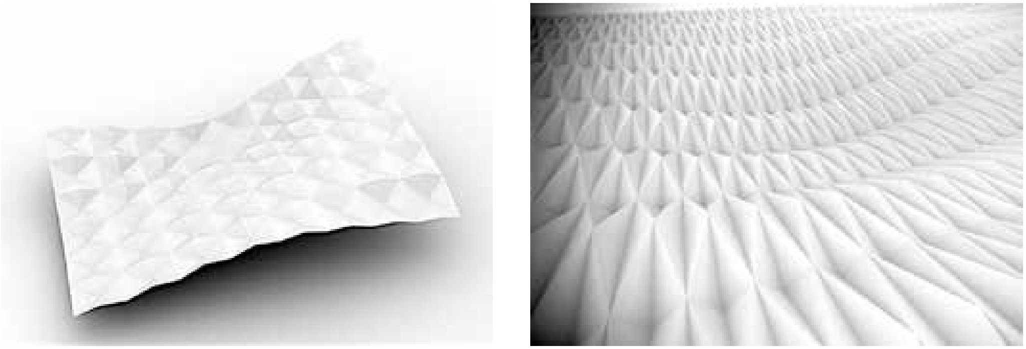


Figure 2
The parametric origami program can transform a flat sheet of paper into a geometric form through various folding techniques: basic techniques (Yama-ori, Tani-ori, Nakawari-ori, Kabuse-ori), advanced techniques (Jyabara-ori, Miura-ori, Hira-ori and so on).

find unpredictable forms which meet both acoustic conditions and design intentions.

EXISTING RESEARCH

In the existing studies, the use of computational methods for designing concert halls is limited to performing two tasks: acoustic simulations and generation of all possible geometries satisfying various architectural constraints. However, there are few methods for choosing the best geometric form among the resulting numerous alternatives.

In this paper, we apply a computational method not only to acoustic simulation and generation of various possible geometries but also determination of the best geometric form satisfying both the architectural design and acoustic requirements.

CONCERT HALL DESIGN PROJECT

In this paper, we apply the interactive design method to a concert hall design project in collaboration with SUEP architects (an architectural office) and Nagata Acoustics (an acoustical consulting firm). The design method consists of three interactive subprograms: a geometric form-generating program, an acoustic simulation program, and an optimization program.

Geometric form-generating program: the parametric origami program

The first subprogram, the parametric origami program, adopts the idea (proposed by the SUEP architects) that a form is generated by folding a sheet of paper—the traditional Japanese art called 'origami.' The program can transform any surface into a geometric form using the basic folding parameters of the origami folding system: folding lines, folding depth, folding width, folding angles and so on (Figure 2). These are mutually constraining (i.e., not independent) parameters.

The objective of this parametric origami program is to develop a method for finding combinations of origami parameters which generates geometries fulfilling complex architectural constraints (Figure 3). The computer technology enables us to test every combination of parameters in order to find out possible designs that meet certain requirements. In this process, designers are no longer making single geometry but finding design parameters which determines a final form (Figure 4).

Another feature of this program is: if there is no combination of parameters that meet every requirement, then the program provides an alternative

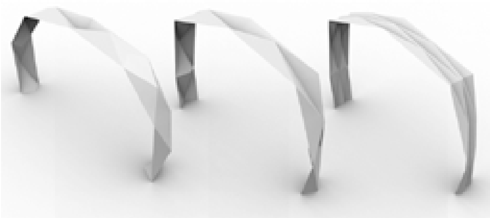


Figure 3
A diagram of generating architectural form fulfilled complex architectural constraints.

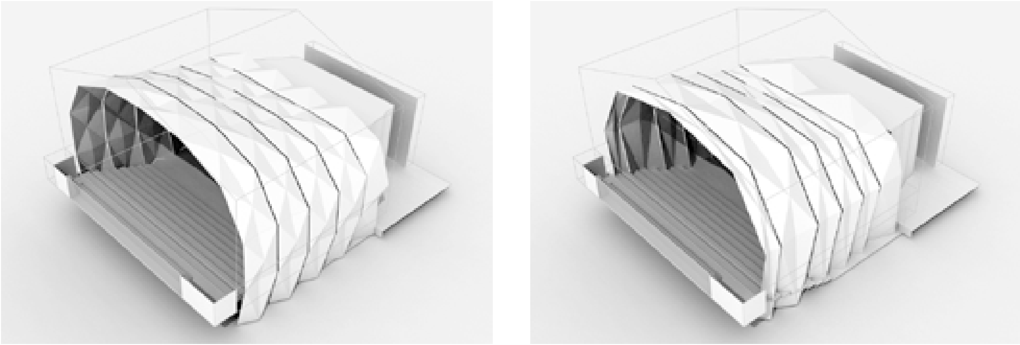


Figure 4
Possible form variations.

combination. In the literature, a few studies deal with computational origami methods for architectural design. Most of them follow a strict origami rule such that a single sheet of paper is fold into a given polyhedral surface without any cut. However, in architectural design processes, this rule sometimes disturbs design intention or other architectural performances. To overcome this limitation, the method enables us to balance parameter weights in an optimization process. That is, the method allows us to cut a sheet of paper or loosen architectural constraints, in the process of balancing between origami rules, acoustic performances and design.

Acoustic simulation program

The second subprogram is an acoustic simulation program, which deals with geometric acoustics, i.e. sound propagation in terms of straight rays.

There are some existing software packages which can simulate sound propagation and geometric forms interactively. However, it can simulate only the distribution of direct sound, which is not enough for sound optimization of a concert hall. To overcome these limitations, we developed an acoustic simulation program which visualizes sound propagation in a three-dimensional space over time in three ways: by arrows originating from a sound source at an arbitrary point in a hall; the distribution of reflected sound; and the distribution of reverberating sound (Figure 5).

These two subprograms, the acoustic simulation program and the parametric origami program, run interactively in the following manner.

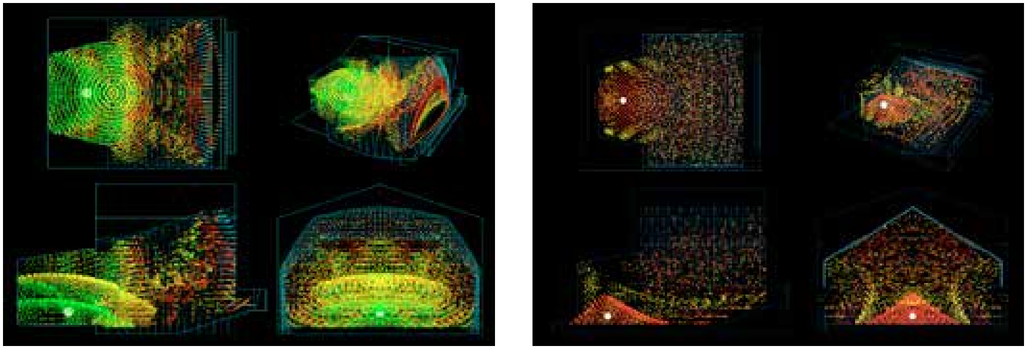
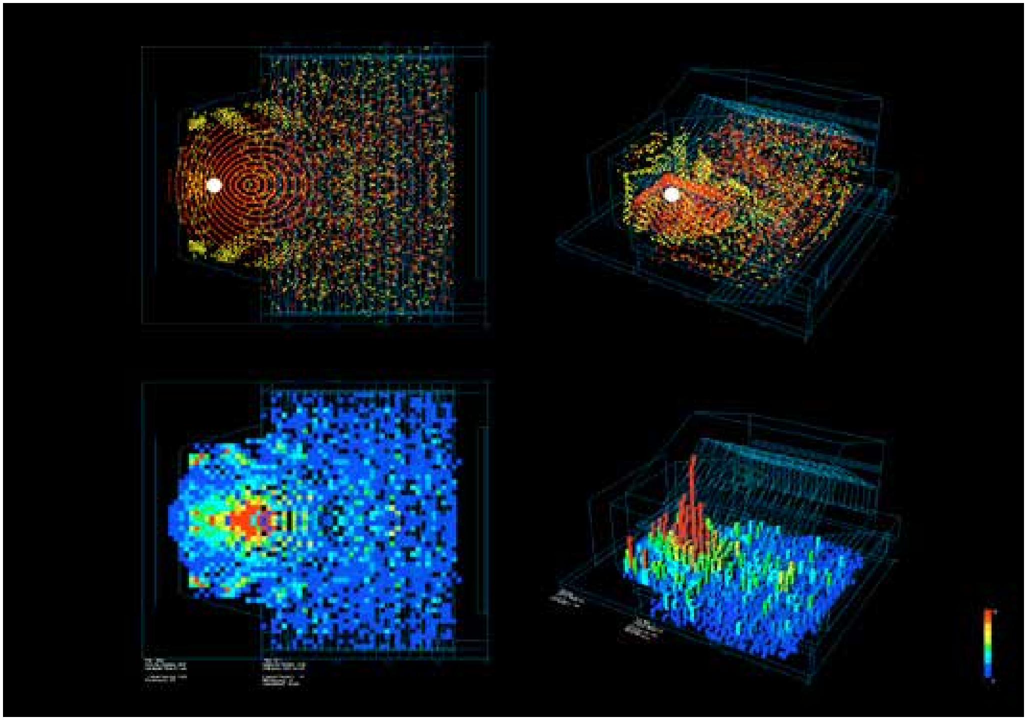


Figure 5
Left: reflected sound simulation, Right: reverberating sound simulation.

Figure 6
Distribution of sound density.



Optimization program by the quadrat count method

First, the parametric origami program generates all possible geometries of a hall according to the parameters derived from the architectural conditions (resulting from building regulations, structure, construction processes, budgets and so forth), the folding parameters determined by the architect's aesthetic sense and allowable parameter values derived from the origami folding system. Then, for each possible geometric form, the acoustic simulation program visualizes sound propagation and the distribution of sound reached at each audience member's seat (Figures 6 and 7). Given the outcomes of each possible geometry, the optimization program judges which is the best combination of parameters that satisfies both the architectural design and acoustic requirements. Acoustic requirements (proposed by the Nagata Acoustics) include: first, the sound is distributed evenly over the hall and audience seats in 30 to 90 ms; second, there is no echo or flatter echo; and third, there is no sound focus. To examine whether or not sound is uniformly distributed over the hall, we applied the quadrat count method with the Poisson distribution. The program automatically calculates the chi-square value for testing uniformity in each form, given by:

$\chi^2 = \Sigma(O-E)^2/E$,

where O denotes observed values and E denote expected values (Figure 8).

Another notable aspect of the optimization program is that it can easily change the conditions of acoustic requirements which vary according to collaborators. Such flexibility produces various architectural designs in accordance with collaborators.

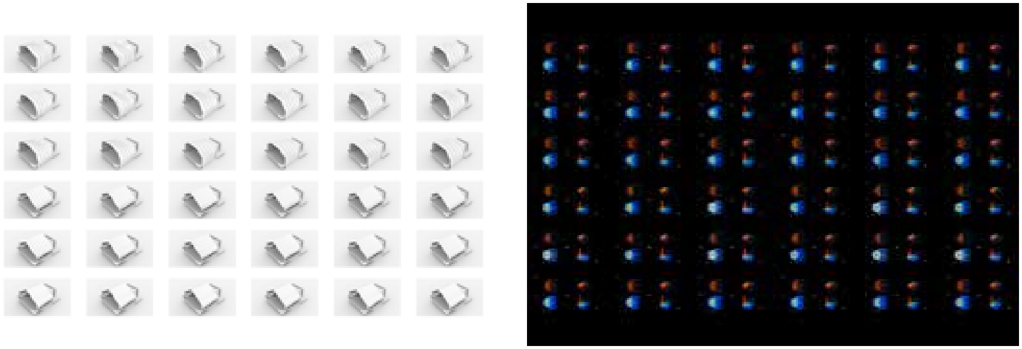


Figure 7
The part of various possible geometries of a hall according to the parameters derived from the architectural conditions, and the results obtained by the acoustic simulation program.

The results of the project

The concert hall design project is part of the design project for a cultural-arts complex in Ureshino-shi, Saga-ken (southern part of Japan). SUEP architects designed this whole project under the design concept of a folding roof. In collaboration with them, we considered that the following three conditions should be satisfied.

- To shorten the processing time for finding variations of origami folding patterns fulfilling architectural constraints.
- To find out a geometric form satisfying not only acoustic performance but also designer's intention. Because following the advice of acoustic engineers often results in a cave-like form (which is acoustically effective) but such a form does not always meet architectural design intentions.
- To discover unexpected geometries which optimize for both acoustic and design conditions.

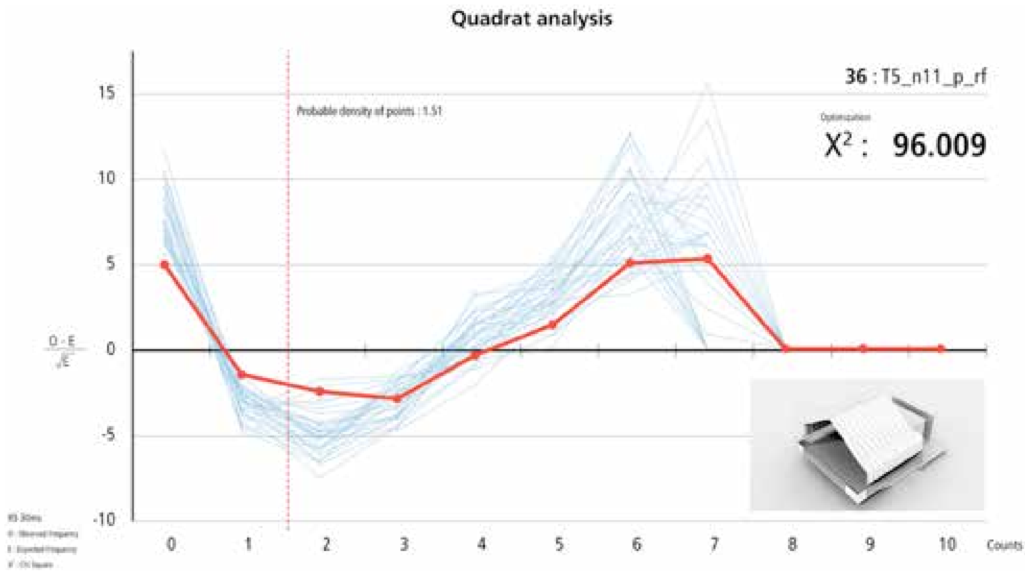
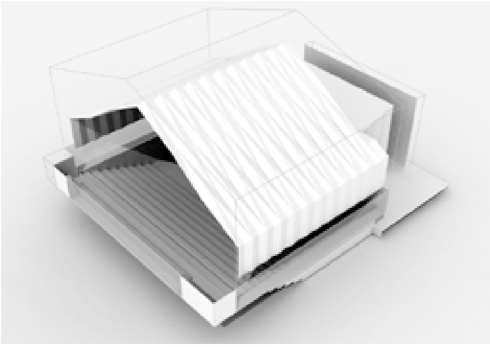


Figure 8
The results obtained by the quadrat method



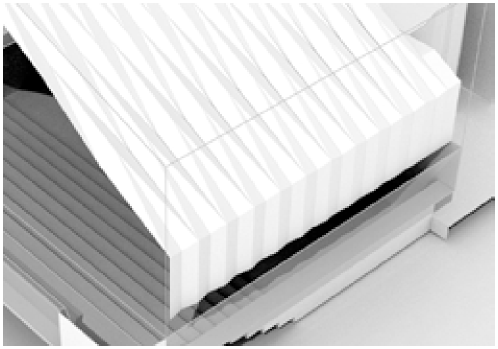


Figure 9
Left: the final model of the concert hall generated by modified Miura-ori taking account of various folding parameters. Right: Details of the final model of the concert hall.

With the proposed computational method, about two hundred possible geometries were generated, among which the final geometry of the concert fall was chosen through the optimization process.

The folding pattern of the final geometry is based on Miura-ori, consisting of concave polyhedral surfaces. At first glance, the final geometry looks simple but it is complex in the sense that the folding depth and angle are delicately controlled (Figure 9).

CONCLUSION

This interactive relationship enables us to choose the best combination of parameters satisfying both architectural design and acoustic requirements among numerous possible forms. Parametric design is often used to explore complex geometries, but in this method it is used to promote complex interactions of collaborators.

Terzidis (2006) mentioned about a form-making process as follows: "architects and designers believed that the mental process of design is conceived, envisioned and processed entirely in the human mind and that the computer is merely a tool for organization, productivity, or presentation". However, the computational form-finding process allows us to take account of acoustic parameters as one of the primary design materials as well as designer's sense.

Computational technology is not only useful for improving or automating design processes, but it is also valuable for generating new possibilities of architectural form by shifting from a form-making process to a form-finding process.

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A Novel Method for Revolved Surface Infrastructures

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Abstract. *This paper presents an algorithm for the formation of single or double curved revolved surface's infrastructures through standardized parts. Any revolved surface can be generated with only two types of parts, interconnected by a ribbed structure technique. The proposed method differs from the accustomed orthogonal rib structures by the varying angle in-between coupling parts. The algorithm can be customized through several parameters like the number, width of parts and thickness of the material used for the infrastructure. The algorithm also offers an advantageous nesting pattern with minimum loss of material regardless of the revolved surface cross-section.*
Keywords. *Revolved surface; standardization; ribbed structure; contouring; nesting pattern.*

INTRODUCTION

Following the design process, the transformation of a complex shape from the digital medium of computer software into the physical reality through material existence requires a further computation and rationalization (Griffith et al., 2006). The rationalization process, depending on the geometrical complexity of the intended shape, aims for the standardization of parts for possible ways of manufacturing, while lowering the manufacturing costs at the same time. Therefore, the process of rationalization becomes an inevitable part of computational design, as long as the target shape is a non-standard surface and requires non-standard parts for its constructability. By non-standard surface, any surface - single or double curved - that cannot be built through conventional manufacturing and construction techniques, and requires a computational design process for both rationalization and manufacturing is indicated. In the case of non-standard surfaces, the number of units may end up in a large number of unique variations, each requiring an increased degree of computation and a heavy process of production. Therefore, rationalization is required to transform the non-standard parts into standardized ones, in terms of their geometry, variability and economy. Besides rationalizing the surface parts, the infrastructure that builds up the surface also needs a process of computation and rationalization (Figure 1). It is the latter one, the infrastructure of a surface that this study is going to focus on specifically.

This study is an attempt to devise a methodology for producing single or double curved surfaces through standardized parts. This kind of approach can be considered as the primary step for enhancing the current computational processes and bringing forth a novel method for the fabrication of single or double curved surfaces. As Branko Kolarevic states, the production of a surface, whether single or double curved, can be realized through "contouring, triangulation, use of ruled, developable surfaces

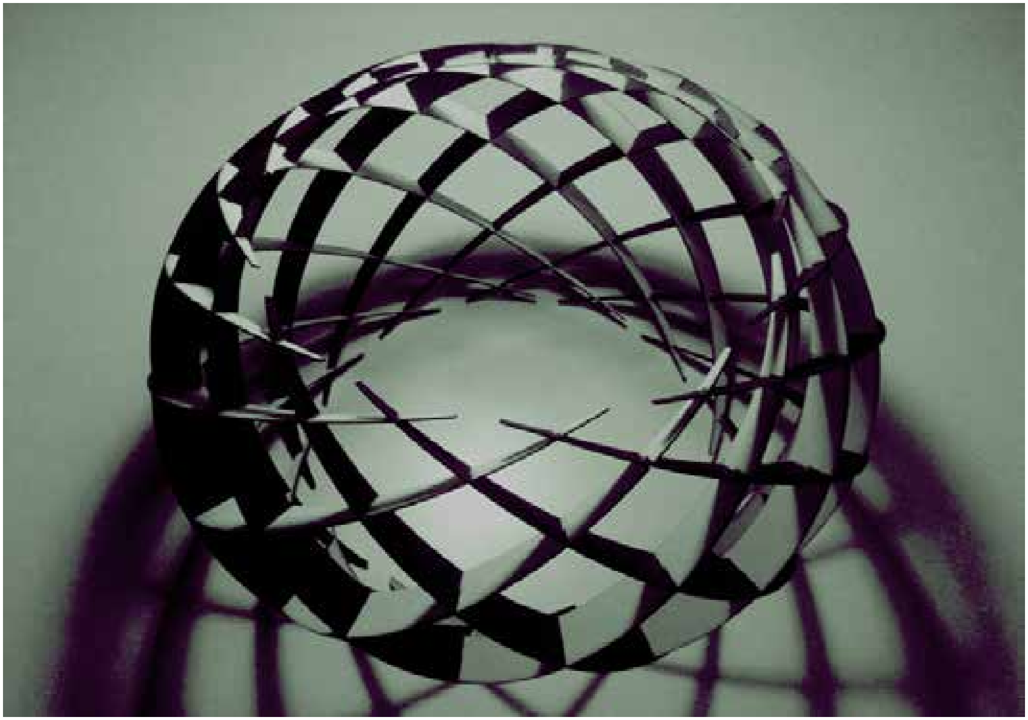


Figure 1
An example of the infrastructure for a spherical revolved surface.

and unfolding" (Kolarevic, 2003, p. 43). The devised method can be regarded as an innovative contribution to the contouring technique *in which the slices are not ran parallel to each other in two orthogonal directions.*

As the starting point of this study, revolved surfaces have been chosen, for their constant curvature along the rotation axis. The constancy of curvature among the rotation axis enables the standardization of parts and apart from the cross-section of the revolved surface, the algorithm generates only two types of parts which form the final infrastructure. The method introduced in this paper focuses mainly on small scale infrastructures, which are possible to be manufactured from sheet materials, like cardboard, acrylic, fiberboard or metal.

The final infrastructure can be denoted as a diagrid system, which is being widely used in architectural projects, especially in skyscraper structures. The environmental and structural factors make it suitable for the diagrid system to be used in high-rise buildings. Therefore, another objective of this paper can be considered as the investigation of possible extensions of the diagrid system through a smaller scale implementation.

RELATED WORK

Apart from the orthogonal ribbed structures, which have been studied and implemented extensively, studies made on non-orthogonal ribbed structures have been analyzed. Agnieszka Sowa's study, at ETH Zurich, explores the possibility of separating parts in relation to each other, for going beyond the scalar limitations of the material and manufacturing techniques. (Sowa, 2004) Sowa's method focuses on generating and optimizing a cubic structure as an instance of many possible forms, through a number of cross-sections integrated through a ribbed structure, by using an algorithm. The parts are manufactured from planar timber elements with a constant thickness. Similar to this study's approach, the variation of angles between the parts has not been considered in Sowa's study, but instead all parts were manufactured by a two-axis CNC milling machine, hence the perpendicular slits, apart from the angle of intersection. The main aim of the study is to devise an algorithm that is capable of generating the intersecting ribs, optimizing the structure through some parameters, separating each rib where necessary and nesting the manufacturing drawings for generating the cutting scheme.

In Kenfield Griffith, Larry Sass and Dennis Michaud's study of generating a strategy for irrational building design, contouring technique is adopted for irrational surfaces, generating horizontal and vertical ribs, with every part different from each other (Griffith et al., 2006, p. 467). While horizontal ribs are located at differing levels with equal intervals and remain parallel to each other, the vertical ribs are generated perpendicular to the surface, ending up with a more complex arrangement. The final structure resembles a waffle slab system used in concrete constructions, projected onto a curvilinear irrational surface. The perpendicularity of horizontal and vertical ribs solves the problem of slit angle variation, thus enabling the manufacturing of the components on a two-axes milling machine. However, it should be noted that the variance among shapes creates a highly irregular nesting pattern.

An ongoing study by Yuliy Schwartzburg and Mark Puly, at Ecole Polytechnique Federale Lausanne, Switzerland, explores the possibility of constructing any shape through intersecting planar shapes (2013). A devised algorithm searches for solutions taking into consideration the cases of intersection and optimizing the intersection angles and positioning of every rib through assembly limitations, slit constraints and material qualities. The study also takes into account the varying angle in-between the parts and comes up with a solution of a predefined maximum amount of variation in the intersection angles. Therefore the firmness of the structure is attained when the assembly of the parts is completed.

ALGORITHM

The algorithm was devised through a script written in Autodesk Maya's Maya Embedded Language (MEL) and later re-implemented in Rhinoceros and Grasshopper plug-in. It produces the production drawings of the parts of the infrastructure and they can be manufactured by a two-axis router, laser-cutter or water jet, for the planar quality of the parts at the current stage of the study.

The algorithm starts with a cross-section curve on the XY plane for the revolved surface, where Y-axis is the axis of revolution; hence farther the curve to Y-axis, larger the revolved surface will be. The cross-section curve should not intersect the Y-axis for the preservation of tubular quality of the revolved surface. Additionally, because of the limitations of the infrastructure, the cross-section curve should pass the horizontal line test, i.e. a line in X direction should intersect the cross-section only once at any point, however a line in Y direction can intersect the cross-section any number of times. By revolving the cross-section around the Y-axis for 180˚, a revolved surface is formed.

The surface is then intersected by a plane lying in the YZ plane and inclined through Z-axis. The degree of inclination is the first parameter of the infrastructure. To guarantee the infrastructure coverage of the whole revolved surface, the intersection points of the plane and the revolved surface at the top and bottom points should be checked, and the angle of inclination may be lessened in order to fully intersect the revolved surface.

The resulting curve of the intersection is copied towards the Y-axis with a certain distance, the parameter for the width of all infrastructure parts, and two intersecting curves form the main constructive element by lofting to generate a surface. The resulting surface is arrayed radially N times around Y-axis with a total angle of 360˚, where N is the third

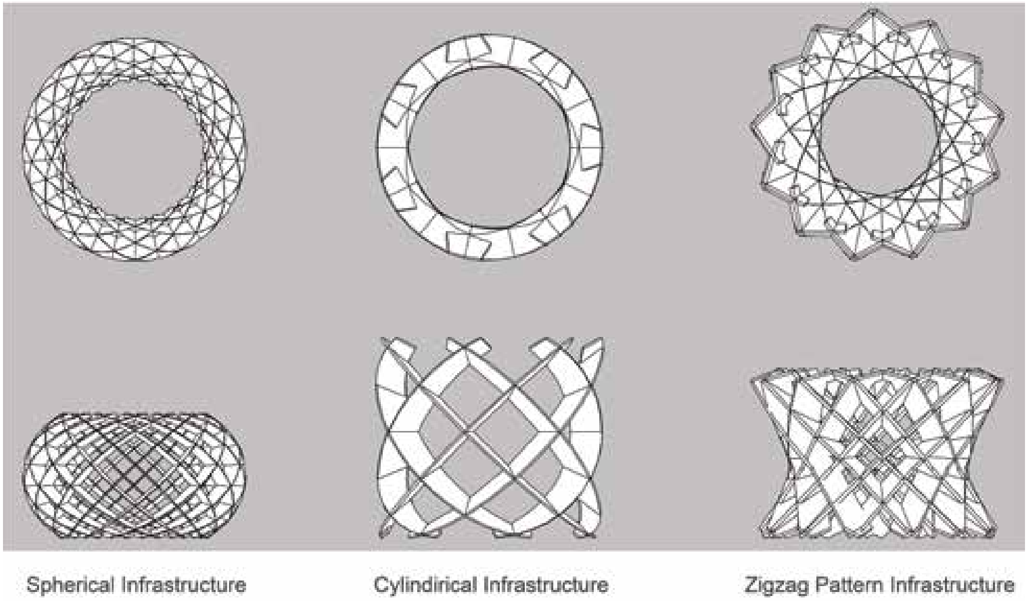


Figure 2
Three examples of the infrastructure.

parameter of the infrastructure. By mirroring the resulting surfaces across XY plane, the infrastructure is formed by planar elements with a total number of elements of 2*N.

Beyond the computation of the slit dimensions, thickness of the material is also useful for visualization purposes (Figure 2). By extruding the parts with thickness of the material, the infrastructure is basically formed, except for the slits.

Each part consists of a number of intersections depending on the formal characteristics and size of the cross-section, degree of the inclination angle and the number of elements. The inclined nature of each part results varying intersection degrees, but they are limited to the number of intersecting parts, i.e. if each part has 7 intersections, the model will have a maximum 7 varying angles at total. To determine the position and size of each slit, angle between the parts and thickness of material are used. The diagram shows the mathematical relation between the intersection angle and the slit width (Figure 2). With the intersection angle decreasing in-between the parts, slit width increases and a 90˚ intersection produces slit width equal to the material thickness.

ADVANTAGES, LIMITATIONS AND FUTURE WORK

When the same revolved surface is produced through orthogonal ribbed structures, in which parallel horizontal and axial vertical sections are used to generate the infrastructure, the method introduced displays some advantages. First of all, the devised algorithm guarantees that there will be only two types of parts to generate the infrastructure. However in orthogonal ribbed structures, while the vertical sections will be identical due to the revolving quality of the surface, the horizontal sections differentiate according to the cross-section, all being circular. Additionally, for all of the slits are parallel to each other on every part, stability of the infrastructure depends on the frictional forces or the infrastructure requires additional elements to fixate the parts; whereas the introduced method has the advantage of interlocking itself due to the varying directions of each slit. Moreover, the standardization of parts also allows the perfect nesting in the cutting scheme regardless of the shape of the final part or the cross-section of the surface (Figure 3).

For the structural quality of the infrastructure is not crucial in small-scale implementations and material efficiency has a higher priority over structure, in the algorithm the intersection curve is not offseted to attain a constant width among the curve but instead copied towards the Y axis. As a direct outcome, the parts have varying width throughout, but on the contrary they can be nested in the production drawings regardless of the initial cross-section of the revolved surface. Additionally, as the nesting pattern also allows a lossless configuration of the parts, routing time is also decreased by the shared edges in between the parts. As long as the manufacturing techniques allow, instead of cutting each part separately and producing left-over material inbetween the parts, the parts are arranged perfectly without any loss of material. However, it should also be noted that this kind of approach may bring forth structural inadequacies, for the uncontrolled variance in the material widths. Nevertheless, the nesting algorithm may be updated depending on the structural necessities for each case, still protecting the advantages of the lossless nesting pattern.

The perfect nesting quality of the parts results in high efficiency in terms of material use when the number of parts being manufactured increase. Therefore, an infinite number of parts manufactured from a roll of steel leads to a 100% material efficiency, which is a distinctively advantageous feature when mass fabrication is considered.

The assembly process follows a relatively simple system of formation. There are only two types of parts, inner and outer. Parts are interconnected to each other through corresponding slits, i.e. first slit to first, second to second and so on. For the varying direction of slits, assembly process is a bit problematic at the beginning when only a few number of parts are assembled. With the increasing number of parts, the infrastructure becomes more interlocked and around the implementation of 70% of the parts, the interlocking becomes completed. It should be noted that the elasticity of the material used plays an important role for the different directions of the slits. While assembling the infrastructure, the parts need to be bended to a certain degree for joining them. This property also ensures the interlocking of the infrastructure. Bendable elastic materials like acrylic, medium-dense fiberboard (MDF), spring steel or cardboard suit well to the infrastructure.

If two-axis manufacturing techniques and thick materials are used for the infrastructure, the surface quality will be highly coarse. This can be better visualized by increasing the thickness of the material in the algorithm (Figure 4). Additionally, ribbed structure technique has a problematic slit connection in cases other than the parts are intersected perpendicularly. Both problems may be overcome through the use of thin materials and further manufacturing techniques. The algorithm is capable of generating the exact three dimensional model for precise interconnection between parts, resulting from the varying degrees of intersection. Therefore, when the parts require a higher degree of precision, a five-axis milling machine becomes more adept. Instead of planar pieces, five-axis milling machine will be able to incorporate the surface curvature of the revolved surface into the parts through thicker materials, besides the angle variations in the slit connections.

Another possible manufacturing method, and maybe the most suitable and optimized one for the infrastructure is the use of injection molding technique. As the number of parts required for the implementation of the infrastructure is limited only to two, in cases of mass-production of a specific cross-section, the manufacturing of two molds will be enough. Together with the decreased manufacturing times and costs, the precision of the final infrastructure is achieved through the use of molding.

Since in its current formation the model does not offer any structural properties, there should be further studies for the optimization of parameters in terms of structural criteria. Number of elements, width and thickness of parts, degree of inclination

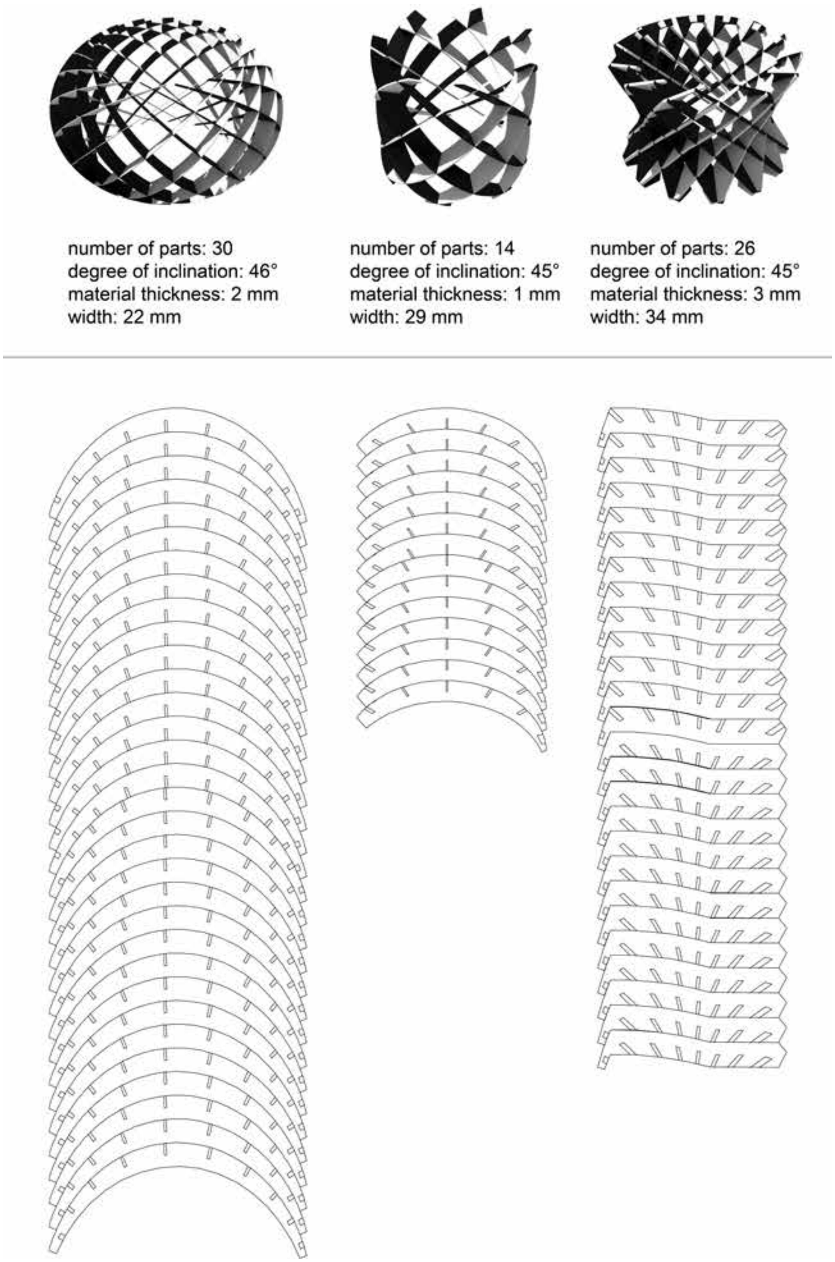
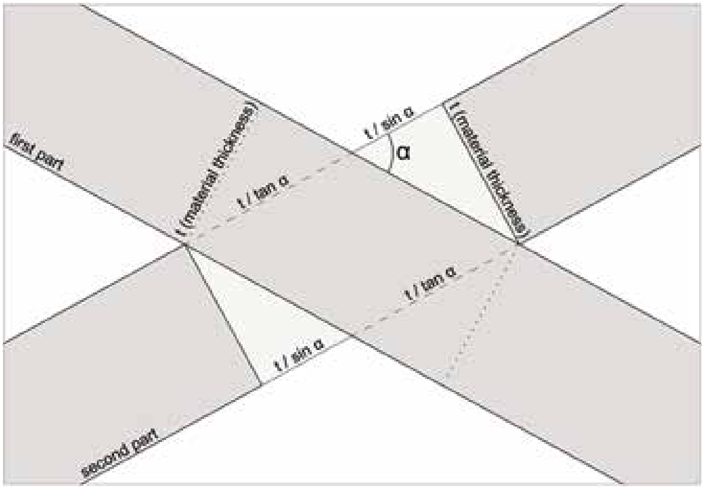


Figure 3
Visual representation, parameters and nesting patterns of the previous three examples.

Figure 4
Slit width calculation formula.



should be tested and analyzed structurally to find out the structural advantages and deficiencies of the method. Alterations to the algorithm may be introduced according to the findings about the structural behavior of the infrastructure. Additionally, the setbacks of the varying width may be studied as an outcome of the structural findings, together with the nesting possibilities apart from the algorithm's current potentials. Consequently, material limitations may be overcome and larger prototypes and implementations may be further achieved. For attaining larger scale infrastructures, Sowa's techniques may be adopted (2004). By dividing each part into sub-parts and connecting them with additional elements, dimensional restraints may be extended.

CONCLUSION

Apart from the formal qualities of the form, standard or non-standard, through designed methods and techniques, the part can be rationalized. The proposed algorithm shows an example of rationalization of a non-standard surface through computational processes and attaining standardized parts. In a larger scope of context, this study proposes an inquiry into the relation between individual part and overall form, together with their integral relation in between, which cannot be separated in any phase of the design process. This attempt reflects an understanding of an approach, which prioritizes the potentials of rationalization from the initial steps of the design process, while also taking material considerations into account.

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Ruling Im/Material Uncertainties

Visual representations for material-based transformations

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Abstract. *Visual rules are powerful in loosely capturing the impact of material behavior on form in designer's hands-on experimentation. They present a first step to translate the causal relations between material and form to computation without sacrificing the uncertainties in the designer's interaction with the materials. This study investigates how to model the relation between material and form with visual rules so that the model embodies some of the phenomenological aspects of reality, rather than merely reproducing it.*
Keywords. *Digital materiality; physics-based modeling; abstractions; visual schemas; shape studies.*

INTRODUCTION

Recent developments in programming and digital production technologies create a new consciousness within the architectural profession, yielding to new design methodologies. The high level of product precision in digitally calibrated fabrication requires a high level of precision in design representation. This numerical certainty finds its expression in mechanistic design approaches that make use of quantifiable, solid data for performance and optimization. However these approaches mostly adopt the limitations of existing computational techniques instead of exploring design beyond the limits of the quantifiable phenomena.

Digital representations that are constructed with mathematical descriptions of the physical object are only capable of reproducing some part of the reality. The description of a reality limited to its known finite qualities is insufficient for the designer who alters this reality in direct and indirect ways throughout the design process. The designer either interacts with the materials on an immediate level or builds a system of different materials and lets them interact with each other while s/he acts as the observer and the controller of this process. The alteration of the designed form based on these interactions is phenomenological, in that it involves the interpretation of various instances of the materials that are "transcomputable" (Glanville, 1998). In this paper we focus on incorporating the founding relations (Rota, 1997) of form and material to address the interpreted in design representations through visual schemas (Stiny, 2011).

In the following paragraphs we discuss digital and physical experiments. We review preliminary studies firstly in the physical modeling of plaster in elastic formwork and secondly in visual abstractions of this process in different digital modeling approaches. We then develop and present a set of visual schemas to illustrate the physical processes in material based transformations.

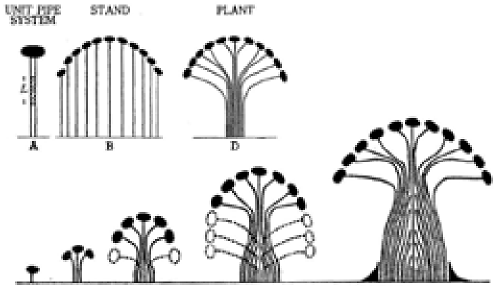


Figure 1
SANAA, House, New York, USA, 2008. Image source: [1].

Figure 2
Pipeline Model of a tree: Diagrammatic representation showing the progress of tree growth. Image source: (Shinozaki, 1964).

ABSTRACTION IS CONTEXTUAL

Abstractions employed in representations are important tools when communicating contextual aspects of represented objects. Building an abstraction requires being selective for features that suit the purpose of a representation. For example there are many ways to represent a tree in the physical model of an architectural project. Sometimes it does not even have to look like a tree in order serve the purpose of being a representation of a tree. In the model shown in Figure 1, the house is surrounded by a blurry transparent nature. That nature is represented with individual trees made of a transparent material. The house is visible through the trees. Transparency is an instance of features one could attribute to a tree. It may not be an absolute property of a tree but in a particular setting how we experience it. Through such an illustration of the tree, its relevance to the context and the designer's intent is communicated.

Differently, a plant ecologist's diagrammatic pipe model of the tree form reveals the relations between the plant's growing patterns and the environmental factors (Shinozaki, 1964). This metameric conception of the tree form divides it into its supposed longitudinal parts "*unit pipes*" that have similar growth behavior and illustrate mechanical properties of the plant (Figure 2).

In each example key features of the tree are defined in relevance to the context and these features are used to build abstract schemas. Both types of models, the scientist's and the architect's are enriched by these types of schemas, in that they make exploration and discovery of new realities possible. The representations we seek in our investigation are similarly selective, being particularly based on the material context, instead of being quantitatively accurate models.

PLASTER SHAPED BY FORCES ACTING ON ITS CONTAINER

The research presented in this paper started as part of a graduate design studio where students conducted experiments to trace the emergent properties of various materials. Drawing from one of these experiments, observing the behavior of plaster in elastic molds of party balloons, authors investigate novel ways to represent form's material causality.

Hand as a Mold

In the preliminary modeling exercise, plaster filled balloons are individually shaped by hand, to be later modeled in the digital environment. This way a direct interaction with the composite material system is provided in the physical experiments. Different shape transformations are observed as different actions of the hands are tried (Figure 3). Digital models are constructed based on the examination of the end products of the physical experiments.

The transformations of the elastic surface are digitally modeled (in Rhino with the Grasshopper plug-in) with a series of straight lines and attractor points that control the geometry of each line. Lines define the surface to illustrate topological transformations of the elastic material in cross-section. As lines morph due to the position of the attractor

Figure 3
Squeeze, pull, twist, push.

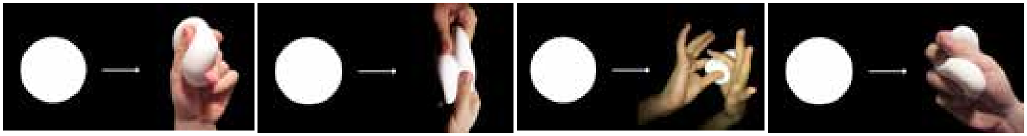
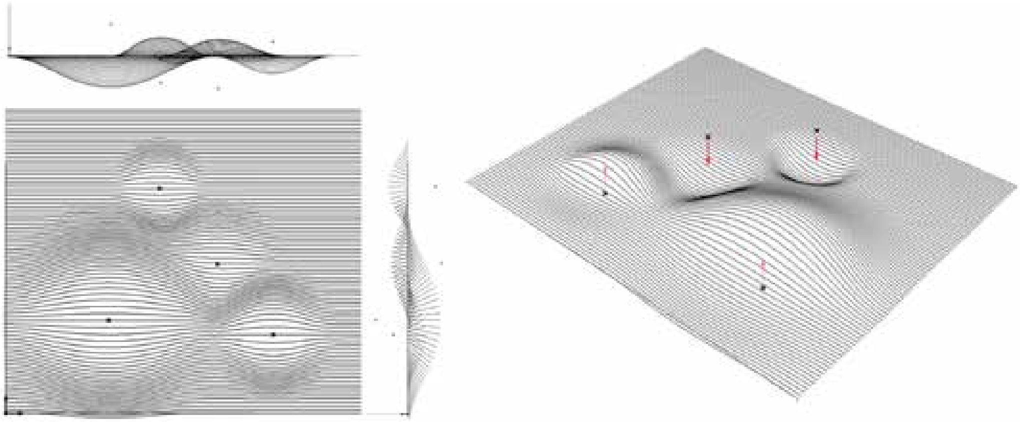


Figure 4
Grasshopper model representing liquid transformations.



points, the density of the lines locally changes (Figure 4). The actions of the hands are to a certain degree abstracted in attractor points. The smoothness of the movement caused by the pressure of the liquid on the elastic surface is acquired with a cosine function. The shape of the bump on the surface could be determined by changing the parameters of the function. In this case the key features of the transformation process that are used to construct abstract models are smoothness of the liquid movement and flexibility of the elastic surface.

Rather than being the exact reproduction of the physical models, the digital model is meant to simulate the interaction with the modeled object. In order to achieve similarity, the manipulation of the digital model must to some degree correspond to the physical material transformations. In the physical environment the designer is able to touch the materials that s/he is working with; this is a direct way to interact with the materials. Commonly used method of attractor points in the digital models is a way to "*touch*" the models in the digital medium. Still it happens on a symbolic level, and is not as straightforward as it might appear. In order to change the shape of the model by moving the points around the scene, first a mathematical description of the change needs to be made and then the attractor points' relation to the change needs to be defined. Furthermore, if the user of the plug-in is not very familiar with the analytical descriptions of shapes s/he might have difficulty in controlling the shape changes. Throughout the design process every time the designer changes the model, the model is reevaluated based on the design objectives. This kind of an evaluation comes mostly from intuitive aspects of seeing, and as Stiny (2006) suggests "*seeing and drawing work perfectly without rational (analytic) thought*". In computation, analysis is valuable when coupled with seeing. Hence, our analysis aims to sustain the phenomenal aspects in the designer's interaction with the material.

Cellular Interaction

In subsequent investigations, conducted as group work in the graduate studio, plaster-filled balloons are put in a rigid mold and their interactions with

Figure 5
Physical models.

each other and the surrounding rigid mold are observed. Different experiments are held changing the parameters, particularly the number of units in the rigid mold and the amount of fluid in one balloon. The circumstances that caused the shape change are examined in connection with the morphology of the end products (Figure 5).

Two digital models for the project were generated with Grasshopper and Softbody plug-ins of Rhino and of 3dsmax respectively. The end results were very similar as shown in Figure 6. Grasshopper model was generated in a top-down manner by dividing a whole into its part. In this case the modules are handled as parts of a whole defined by the geometry of the rigid mold and division rules of Voronoi tool. In Softbody each module is treated as a consistent whole with predefined properties. Their interaction with each other and the rigid mold is simulated through the behavior of each module.

Softbody plug-in of 3dsmax is a physics-based modeling environment and its interface allows the user to control the material behavior of the modeled objects by changing the parameters like stiffness, damping, friction and the gravity (Figure 7). Physics-based modeling approaches like these have proven to be useful when building lifelike representations of the materials with in the design process. Principally a physics-based modeling environment

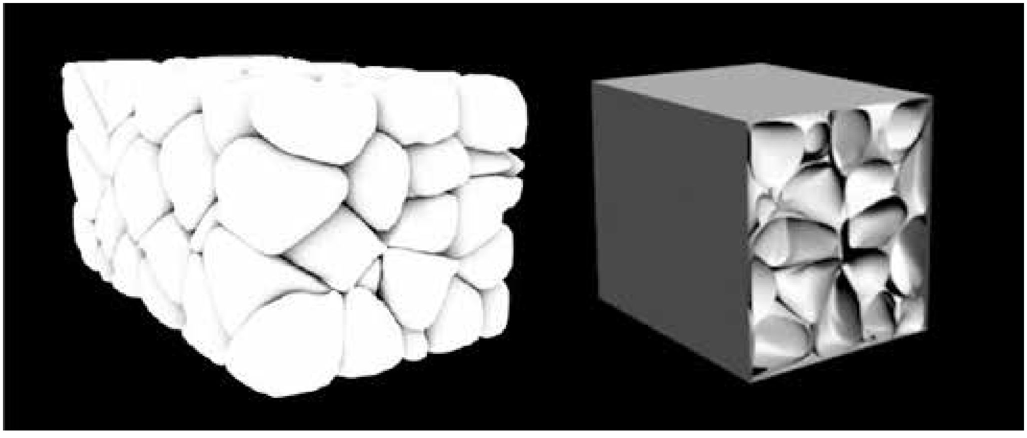
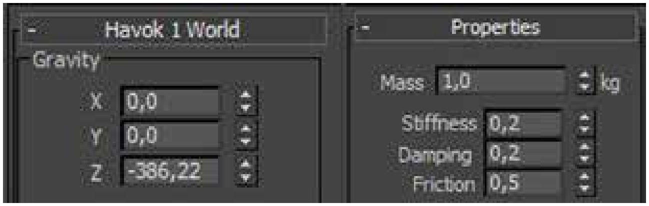


Figure 6
Digital models: from left Grasshopper Voronoi model, 3dsmax Softbody, negative space model.



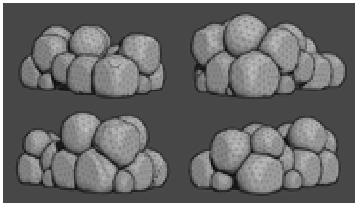


Figure 7
Interface of the Softbody plug-in.

Figure 8
Softbody model.

operate on the basis of a simulation algorithm developed for the physical process it represents and the user interacts with the model through visual outputs. Visual schemas play an important role in physics-based modeling approaches. For example the Softbody plug-in of 3dsmax simulates the elasticity of objects through the principles of particle physics in that the surface of a "softbody" is defined with points which are interconnected with hypothetical springs. With the help of this surface abstraction it becomes possible to model the elastic deformation of materials (Figure 8).

VISUAL SCHEMAS OF PHYSICAL PROCESSES

The models above are attempts at representing material properties that impact form. They are purposefully incomplete exercises that serve to analyze material properties and to see where digital models may fall short. As seen above, each plaster unit is shaped differently. This unpredictable variability in material transformation is a challenge for representations that are expected to support it. We propose visual rules to achieve this. Stiny's (2011) definition of general transformation rules and the unrestricted rules suit the variability in question here. An initial shape schema is crucial with parts that could be altered to generate different products of the transformation process. Stiny's (2011) examples of Goethe's Urpflanze and Semper's Urhutte are both archetypal schemas for a class of objects, that are varied and each with definite parts. Our question has been how we can formalize visual schemas for objects without definite parts such as the plaster filled balloons. It is insufficient to observe just the products of the transformation for formalization of such a schema. An examination of the conditions that bring about the transformation is also necessary (Figure 9, 10).

The rules are derived by looking at the transformation process, and the relations between proper-

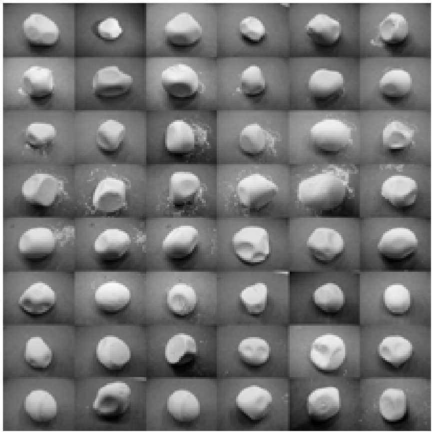


Figure 9
Multiple products of the 'cellular interaction model'.

Figure 10
Cellular interaction model: neighboring components.

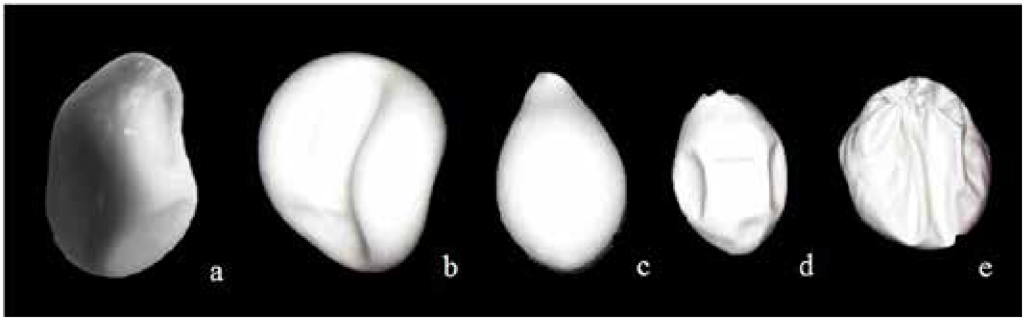


Figure 11
Different processes leading to different morphologies: a) cellular interaction, b) hand as a mold, c) plaster in a balloon: fully filled - no deformation, d) plaster in a balloon: half filled, e) plaster in a balloon: half filled.

ties of the components. Key features among the end products of the transformation process are identified to construct abstract schemas. These common features, when varied, are what make the products unique incidents. Figure 11 shows the results of the different transformation processes for plaster in a balloon. It is clearly seen how both materials circumstantially take the shape of each other. For example in the case of half filled balloons shown in figures 11 d and e plaster take the shape of the creases of the balloon, however in the 'hand as the mold' model in 11 b with the balloon squeezed liquid plaster stretches the balloon rushing away from the pressure of the hand.

To find out which of their parts make them distinguishable as the products of different processes, first these parts need to be determined. It can be simply done with Hoffman and Richards' (1983) smooth surface partitioning rule (Figure 12). According to this rule human vision enables recognition of objects by dividing them into their parts. The minima rule states that this partitioning process takes place based on the discontinuities on a surface (Hoffman, Richards, 1983). With this method we divide the surface of the model in Figure 11-a as shown in Figure 13. Parts are recognizable at the contact areas with the other components and they are either concave or flat (Figure 14).

The geometry of the contact areas are determined by the material properties of the components in the system. When two plaster-filled balloons come into contact with one another, the more rigid one imposes its shape on the other. The rigidity in this case is determined by the two factors: the amount of liquid in the balloon and the physical state (liquidity) of the plaster at the moment of contact. Another factor that specifies the geometry of one object is the number of objects that it is in contact with. When we mark the differentiating surface parts on the contact areas with surface partitioning rule, the polyhedron like structure of the remaining parts of the surface is revealed (Figure14). The more tightly the plaster-filled balloons are packed in a rigid mold, the more angular is the appearance of this polyhedron-like structure. The polyhedron-like structure and surface differentiations at the contact areas are recurring features in each component, whereas the angularity of this polyhedron-like structure and concavity of the differentiating surfaces are varied.

A visual rule illustrates the relation between the shape transformations of each plaster object

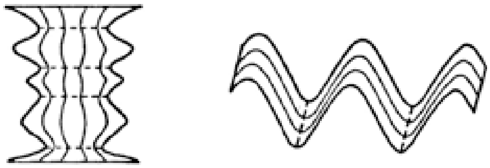


Figure 12
Smooth surface partitioning, "Minima Rule: Divide a surface into its parts at loci of negative minima of each principal curvature along its associated family of curvature." (Hoffman and Richards, 1983).

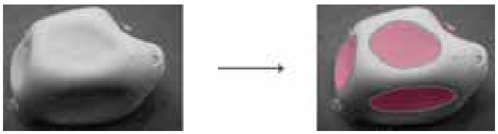


Figure 13
Smooth surface partitioning of the surface of a "cellular interaction" model.

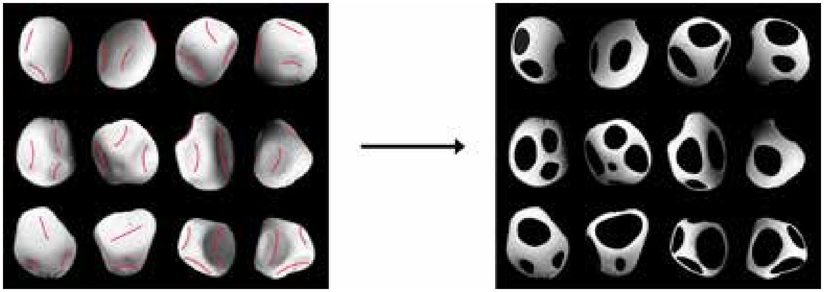


Figure 14
Marking the convex and flat surfaces with smooth surface partitioning method.

and the way they are packed in a rigid mold (Figure 15). In this rule, the initial shape of the plaster-filled balloon is represented with a circle plane. The right side of it shows the transformed shape while the indicator above the arrow gives us information about the context used in the action. The area of the circle plane corresponding to the volume of a component stays the same during the transformation process. Colored lines represent the neighboring units.

We vary this rule to capture emergent properties of the plaster-formwork interaction. The rules in Figure 16 display the condition where the outer rigid mold gets smaller while the number of the units in the mold stays the same. The increase in the angularity of the resulting shape is visible as the surrounding units get closer to one another. The rules in Figure 17 show the formation of polygon-like shape of a unit with the increasing number of surrounding units. It also reveals the relation between the number of surrounding units and the number of sides of the polygon. By changing the position and the number of the surrounding units, different shape computations can show the gradual transformation of a unit (Figure 18).

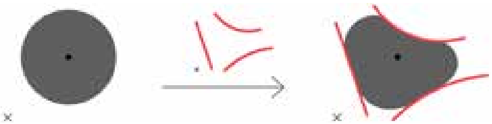


Figure 15
Visual Rule 1: Gray circle plane represent the initial shape of the plaster-filled balloon and. Red lines stand for the surrounding units of a component in transformation.

Figure 16
Visual Rule 1 elaborated: Angularity of the plaster object increases as the volume of the outer rigid mold gets smaller.

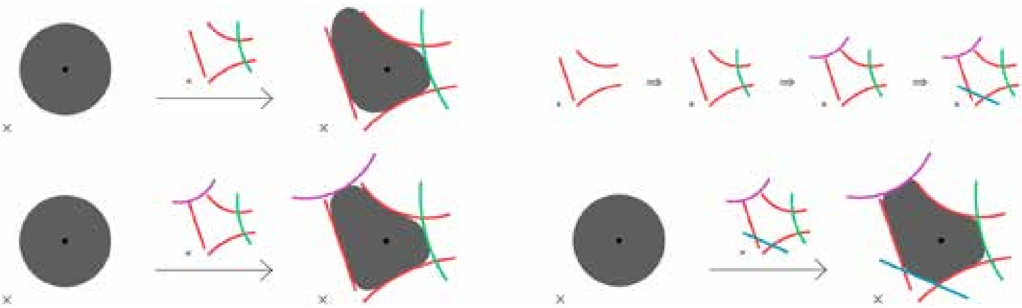


Figure 17
Visual Rule 1 elaborated: Angularity and the number of the sides of the plaster object increase as more balloons are put in the rigid mold.

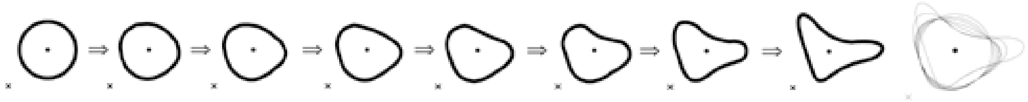


Figure 18
Shape computations showing the gradual transformation of a unit as the surrounding units get closer to each other.

The rules presented in Figures 15-18 give a clue about how shapes come about. Nevertheless, it is not possible to fully comprehend the process by just looking at these. The mold of the surrounding pieces shapes the plaster-filled balloon. The rules present the surrounding units as solid shapes, however this is not always the case. Rules still need to reveal the interaction of the neighboring objects.

Further examining the transformation, it is possible to improve the visual rule to contain more information on the process. That leads us to a less general rule. In Figure 19 the visual rule for the schema x → x – prt(x) + prt(x)' is presented. Here the transformation of the subtracted part of the initial shape is displayed with parametric variation rule under general transformation rules (Stiny, 2011), for the areas of the subtracted and added parts are equal.

To further enhance the rules, properties could be assigned as weights (Stiny, 1992). As the shape transformations are mainly regulated by the rigidity of each component in the system, it is the first material aspect to be included in the visual rules. In figure 20 the thickness of the line signifies the rigidity of the elastic mold while the grey tone stands for the hardness of the plaster. These are depictive rules. In search for alternatives that can be more generalizable, we also develop the visual rules in Figure 21 that serve the same purpose but more generally to work even for singular objects. They exhibit two different cases of *being in a mold*. Based on the rigidity of the components, which is represented with line thicknesses, their potential to transform one another is displayed. Different weights (color and thickness) signify properties that undergo transformations. Shapes are generic and can be interpreted to subsume others.

CONCLUSION

Current digital modeling environments have the capacity to provide the designer some form of interaction with the model but phenomenal aspects of the physical environment often get lost in symbolic reductions. In most cases the designer interacts with the digital models on a symbolic level and forgoes

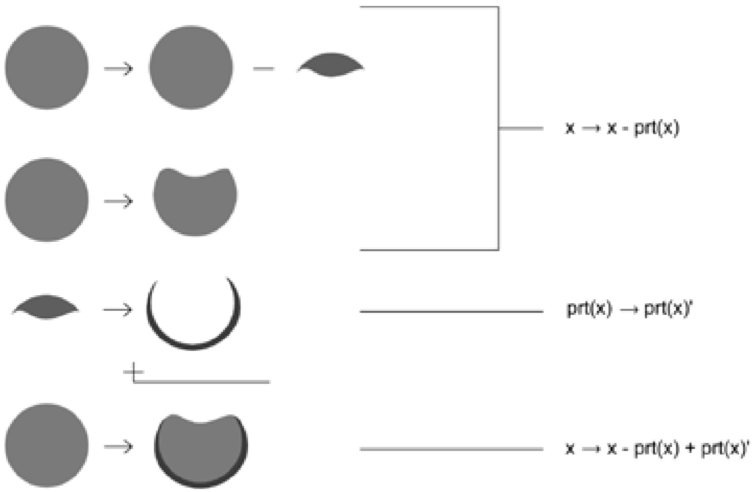
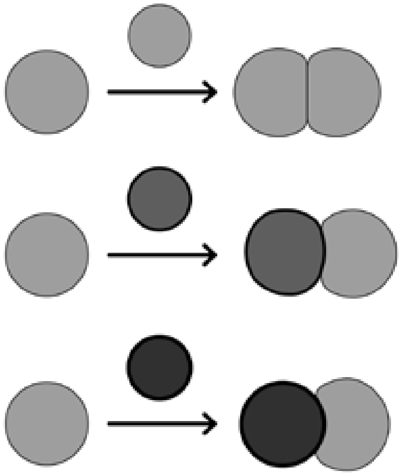
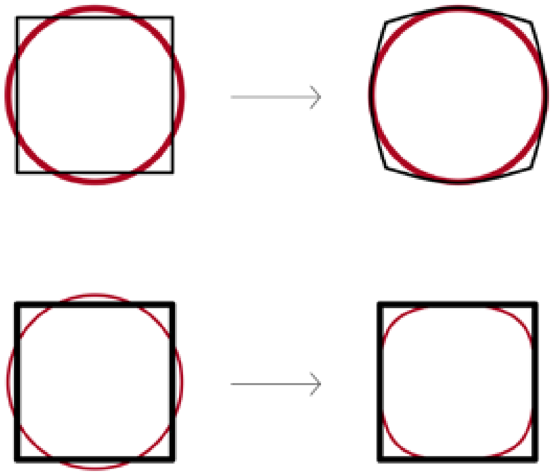


Figure 19
Visual rule of the schema x→ x- prt(x)+prt(x)' .

Figure 20
Weights as tones of gray and line thicknesses. The darker the gray tone the harder the plaster it represents

Figure 21
Weighted shapes representing the rigidity of the boundary of an object. The rigidity increases with line thickness.





the causality shaping the design. In the digital model, the designer is able to perform transformations on the model by changing some numeric values within set ranges. In addition to this capacity, there is a need for case-specific visual rules. This is to embody the designer's unique reasoning which feeds from the interaction with the material. The variation of plaster-in-balloon morphologies in Figure 11 illustrates differences between instances. We study a particular hands-on experimentation in order to showcase how visual rules may document the form-material relation with the aim of supporting the interaction of the designer in the digital form-finding processes. We have developed exemplary rules and schemas as general and visual as possible based on parameters derived from hands-on experimentation. There are many parameters that determine the composite behavior of the materials. In this study, they add up to two main features: geometry (curvature) and rigidity. The values indicating material properties of components are employed in the computations of shape transformations.

The rules given in this paper are in no way a complete grammar but are directives for phrases that can belong to a grammar if a designer wishes. These rules are mere instances of how material based shape transformations can be visualized to be compared with one another, to be manipulated if necessary, and to be understood within a broader picture of how shapes come about. Differently than rules, schemas, as defined and categorized by Stiny (2011), aid in understanding the rules within formal categories that might prove helpful in setting up the support system in the digital platforms. Visual rules, and visual schemas as their more general versions, not only document transformations but also summarize and help systematize the designer's perception of founding relations of actions. Visual rules presented in this paper also utilize weights that can be used to represent magnitudes of certain material properties.

Further research requires applying these kinds of rules for synthesis, as opposed to for analysis, and in parallel to a design exercise as opposed to a material exploration exercise as the one referred to in this paper. This would help us see how the results correspond to the rich interactions the designer has in the material world. Additionally, since visual rules are specific to case and designer but can be categorized using more general schemas, it is meaningful to pursue a system to support various visual rules in the digital platforms.

ACKNOWLEDGEMENTS

The graduate studio mentioned in the text is Digital Architectural Design Studio, a required course in Architectural Design Computing Graduate Program in Istanbul Technical University. The studio was supervised by Mine Özkar and teaching assistant Ethem Gürer in the academic term of Spring 2012. The group work that serves as the object of this investigation was conducted by students Aslı Aydın, Halil Sevim, Ersin Özdamar, and Zeynep Akküçük. The analysis of the experiments with visual schemas are entirely done subsequent to the studio.

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Hyperdomes

Non-standard roofing structures, technological evolution and distinctiveness in urban environment

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Abstract. *The development of new shapes in architecture has deeply influenced the current perception of the built environment. The analysis of the processes behind this evolution is, therefore, of great interest. At least two well known factors, influencing this development, may be pointed out: the great improvement of digital tools and the tendency toward building distinctiveness.*
In particular, the innovation of digital tools such as parametric modeling is resulting in an overall diffusion of complex shapes, and the phenomenon is also evident in a clear expressionistic search for architectural singularity, that some might consider as a negative effect of globalization trends.
Though, if we can consider as a positive result the fact that parameterization allows a deeper control over design factors in terms of reference to cultural, historical and physical context, at the same time such control possibilities are sometimes so stark to be even auto-referential, stepping over site-specific parameterization, to create unusual shapes just for the sake of complexity.
The ever-growing diffusion of generative design processes is in fact going to transform niche procedures, frequently limited to temporary decontextualized structures, into an architectural complexification as an end in itself.
The hypothesis of this paper is to demonstrate that site-specific parametrization can be considered as a tool able to translate intentions into shape; it is necessary, for this aim, the widening of the meaning of the word singularity.
Keywords. *Urban environment; distinctiveness; non-standard roofing structures.*

INTRODUCTION

The need for new shapes in architecture has brought a great development in techniques and processes able to control and manage the building construction. It is worth to focus on two factors of this evolution, the improvement of digital tools and the tendency toward the building distinctiveness. The aim of this work is to define the which digital tools produce distinctive shapes, by analyzing a set of significant case-studies through times.

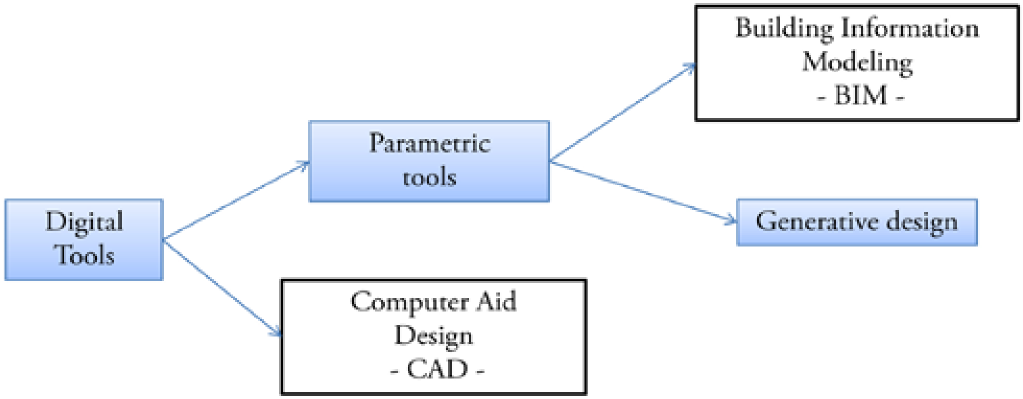

Figure 1
Digital tool scheme. Boxes in blue are the tool families of interest for this work.

DIGITAL TOOLS

We refer to digital tools as a generic expression to define a giant umbrella of different software, which are very different in aims and efficiency. It is therefore useful framing the parametric tools into a narrower family of design instruments. The use of parametric tools for design complex shapes creates new methods, often unexplored, to describe a comprehensive notion of building performance.

The meaning given to parametric tools is worth to be deepened because of relative youngness of this discipline, which lacks of acknowledged notion. There are at least two families of parametric tools that are radically different in methodologies and finalities. The framing applied to this work has been schematize in Figure 1.

The first is the Building information Modeling (BIM), widely used to optimize building performance with a certain degree of constraint. The limit of BIM is the creation of new shapes, which are not pre-build inside the software.

The second family, which is of higher interest for this work, is that corresponding to the so called generative design tools. These digital tools that works in strict connection with coding, which embraces an area of knowledge quite far from traditional architectural design procedures. In this case the architectural form is defined through code, made by declaring variables and constants, by writing instructions, routines and by running an algorithm until the shape which performs better is reached. The final shapes are so produced only by a sequence of instructions that produces a result. The designer isn't the only actor in the shape creation process, because it is paired with the machine results, which might go beyond the starting idea. In fact the initial shape design, might even be developed into something unpredictable at the start of process. So it is essential to focus the attention on the component that directly modifies the production design, which is the code.

The code writing, as an act of creation, corresponding to the designer's intention, gives complete freedom to choose the road to the shape definition. This freedom is partially constrained in controlling the resulting shape, which may go beyond the choice of the preferred shapes. It is so introduced a disruptive innovation in the design process, which changed deeply the ordinary design method.

The ordinary design process is made of a circular correspondence between the mental knowledge of the shape and its final representation. In generative design, instead, the effort is focused in thinking about the code that will produce the shape, until the desired shape is reached. The resulting shape, therefore, is generated with an indirect procedure, not by direct modeling and editing of shape. In this sense, two classes of design process drivers may be outlined, external and internal: site-specific parameters and building related parameters.

USE OF TOOLS – SITE SPECIFIC AND BUILDING RELATED PARAMETERS

Site-specific parameters are made by the elements of the urban environment that influence the building in its components. The effect of these external constraints is evident in some aspect, as the external skin of buildings, but it may influence the structure and the functions of the generated spaces. The application of these specific parameters is important to provide the building with the correct contextualization within the neighboring spaces. It is therefore important to understand the rules that define the urban environment to better set up parameters that will characterize the building, giving it the character of distinctiveness. The use of these elements points out the importance toward building located in urban environments, which are endowed of their own characters, which cannot be ignored.

In parallel with these elements, collected from external environment, it seems important to underline the importance a second class of factors, the building related parameters. These may be defined as the set of relationships established within the geometric elements of the building skin. This approach works perfectly with art installation, which is needful by itself. The aim of this design method is to give a complex and appealing perception to buildings because for some kind of aesthetical need, a lack of intricacy in shape is perceived as a lack by a large part of designers. This need is largely fulfilled by the use of generative design tools, which easily generates an auto-referential complexity. With these specifics, it is easily understandable how the generative-design tools have been pointed as the next -generation step in the evolution of design process.

SHAPE DISTINCTIVENESS

The innovation of digital tools, is one of the two drivers in new shape generation, the other is the tendency toward distinctiveness.

The singularity is intended as a recognizability of a building in an urban environment. It is considered at the same time as internal and external character of architecture that has to relate to imageability of the shape, considering its connection with urban environment.

Internal singularity is related to the distinctiveness of structural and technological performance of architecture which makes exceptional a building in itself. External singularity, instead, is the recognizability character of the architecture on a larger scale, making it a relevant element of the urban environment. A parallel can be set with the relation between internal and external singularity and the aforementioned connection between building-related and site-specific parameters, as pointed out in Figure 2. The strict relation between the tools for form-finding and the pursued aim creates a disruption in the process of singularity creation. The linear process where tools creates the singularity is transformed into a design loop where tools create complexity, and the singularity generates new parameters to drive the software.

Despite the tools limitless shapes creation, their complex approach and the steep learning curve, keeps away from the use outside academia and top-notch designer.

So that most of the buildings created with the generative process are endowed with internal singularity because they are small-scale architectural manufactures, pavilions and temporary installations that are designed intentionally ignoring the connection with urban environment.

This tendency toward singularity wasn't so definite through the times. It is to be underlined, in this sense, the denial of monumentality, in Le Corbusier's architecture.

Therefore it has seemed uncompleted conducting an analysis of this phenomena, limiting the analysis to contemporary buildings endowed with external and internal singularity, so it was chosen to consider the domes, which have always been distinguishing elements of verticality emerging in horizontally dominated urban environment.

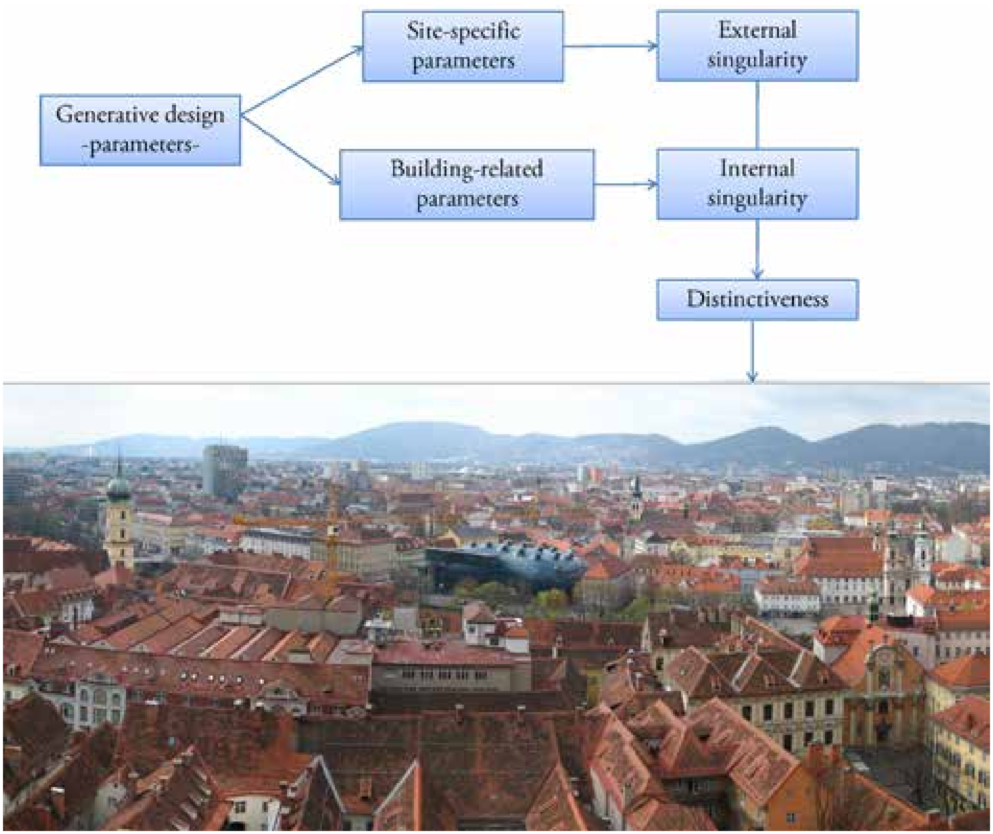

Figure 2
Shape distinctiveness: the case of the Kunsthaus emerging in the roofscape of Graz.

FROM DOMES TO HYPERDOMES

The meaning of dome, intended as a "large hemispherical roof or ceiling" (Merriam Webster dictionary) has a deeper significance connected with the its function in the past. In fact the spaces too wide to be covered with normal ceilings, were closed with hemispherical roofing structures. One renowned example of these issues is the cathedral dome of Santa Maria del Fiore in Florence. The base of the dome was built in 1315 and it remained unfinished until 1436. It took more than 100 year to be finished because at that time nobody was able to design a cover for such a span of space, until Brunelleschi, in 1418 conceived a series of structural and strategies to achieve such aim. The dome issue is shown in Figure 3 in which Andrea di Bonaiuto, painted the Church before Brunelleschi's design. The depicted dome is a fake because in 1350 there was no built dome, just designs. because of the complexity of the aim. Therefore Santa Maria del Fiore dome may be considered as a reference example of non-standard roofing structure clearly emerging in an urban landscape. Further Case studies for these past domes are the XVII century Sindone dome by Guarino Guarini in Turin (Figure 4 left) and the XIX century San Gaudenzio Church dome by Alessandro Antonelli, in Novara (Figure 4 right).

Figure 3
Detail in Santa Maria Novella from " Spanish chapel" 1350. Santa Maria del Fiore is depicted with a fake dome because it wasn't possible at that age to build a real one.

HYPERDOMES

The domes as a symbol of this phenomenon have been transformed through times into a more complex form of architecture, rather similar to a singular roofing structure than to a classical structural element. In this work the non-standard roofing structures (as architectural elements to be considered in the broader sense) are acknowledged as key elements to select specific study cases, where the higher level of complexity of non-standard structures can create points of singularity within the context.

When it came the need to define these special non-standard domes, it was necessary to specify a word for structural elements which were a compromise between geometrically defined domes and mesh structures. Therefore the term "hyperdome" will be used in this work to widen the meaning of domes including all the roofing structures which creates singularities in urban skylines.

As traditional domes produced a break in the skyline of cities in the past, so hyperdomes make a rupture in actual urban context. The singularity that characterized domes of the past is not limited to urban environment, because they represented both technological excellence and structural innovation at their time. We could also refer to more examples, such as the Pantheon in Rome, S. Sofia in Istanbul, the Antonelli Mole in Turin, the works of Boullée or Speer, Nervi and Buckminster Fueller in recent times, but we try to limit our attention to some cases of specific relationship between the digital innovation produced by design tools and its translation into distinct shapes. Similarly, new generations of contemporary "domes", hyperdomes are landmarks in the skyline, because of their shape and structural singularity, so they get imageability (in the meaning attributed

Figure 4
Churches of XVII century Sindone dome by Guarino Guarini in Turin and XIX century San Gaudenzio Church dome by Alessandro Antonelli, in Novara, relevant prototypes of hyperdomes clearly marking the urban and, for the latter, even regional landscapes.

to this term by Kevin Lynch (1960), as a "quality in a physical object which gives it a high probability of evoking a strong image in any given observer").

In this sense, that might seem not only challenging but even provocatory, some case studies for contemporary structures are the Future Systems' Selfridges building in Birmingham (Figure 5), the Kunsthaus in Graz by Peter Cook and Colin Fournier (Figure 2), the Opera House in Lyon by Jean Nouvel (Figure 6), the Greater London Authority building (Figure 7), British Museum Great Court in London (Figure 8) and Reichstag in Berlin (Figure 9), all by Norman Foster, the recent roofing structures in Gent and Taiwan (Figure 10) and Meiso no Mori funeral hall in Kamigahara (Figure 11), by Toyo Ito and the Lingotto dome by Renzo Piano (Figure 12).

CONCLUSIONS

This study has analyzed the aforesaid series of case studies, pointing out how the new relationships between design tools, structural conception, shape innovation, contextual references and symbolic values become key factors to understand the evolution of hyperdomes.

Starting from the given hypothesis this paper has shown a possible interpretation of the current interpretation of domes and how both the internal and external singularity may be considered for giv-

Figure 5
Selfridges building in Birmingham - Future Systems. The hyperdome creates a singularity by integrating itself in the urban environment though being a complex shape.

ing the building a shape distinctiveness in the urban context. A positive or negative assessment of the role of hyperdomes goes beyond the aim of this paper that mainly aims at recognizing and interpretate the phenomenon of the complex shapes in terms of relationship to the urban context, without involving aesthetic and historical issues that deserve further and specific disciplinary attention. Nevertheless, it

Figure 6
Opera Nationale de Lyon – Jean Nouvel. A contemporary dome, which creates a singularity in urban environment.

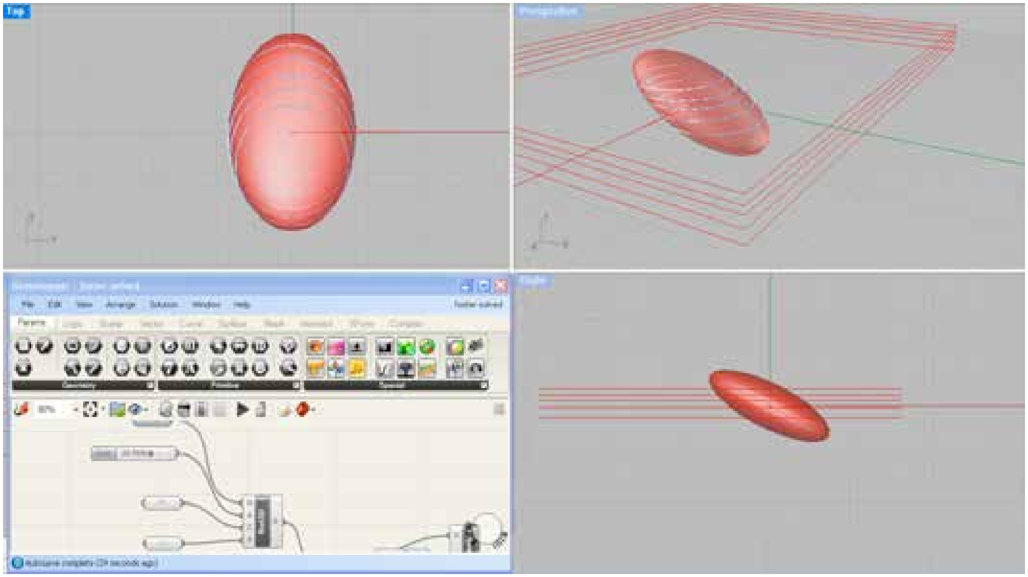

Figure 7
Greater London Authorith builing - Norman Foster. Geometric singularity by the discovery of the only rotation angle that creates circular section from a elliptical ellipsoid.

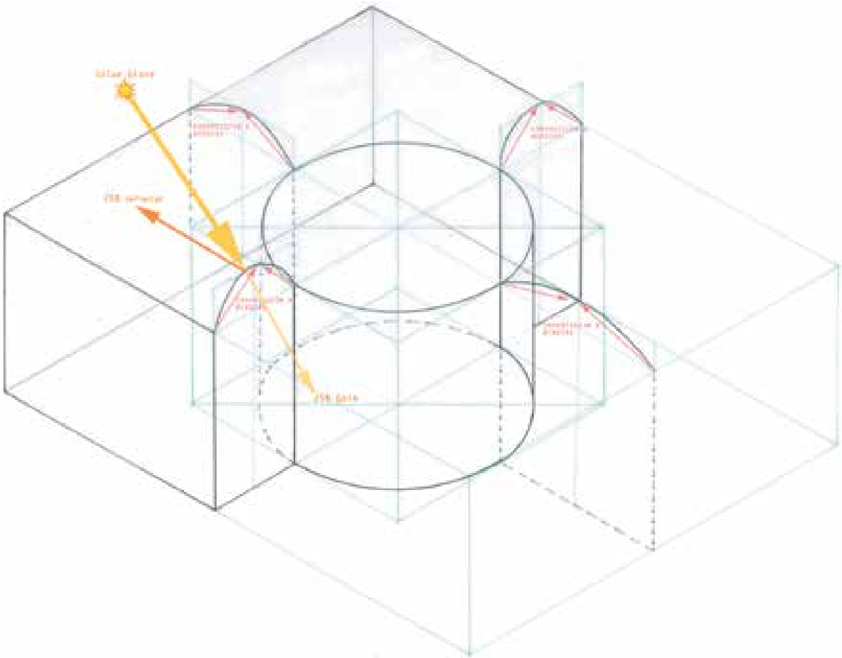

Figure 8
Queen Elizabeth II Great Court at British Museum, Norman Foster. Structural singularity. Effects of compression and bending must pass through the nodes in all directions, decreasing bear loading of central building. Green performance is achieved through the glass perceived as clear, which is shielding 75% of ultraviolet rays.

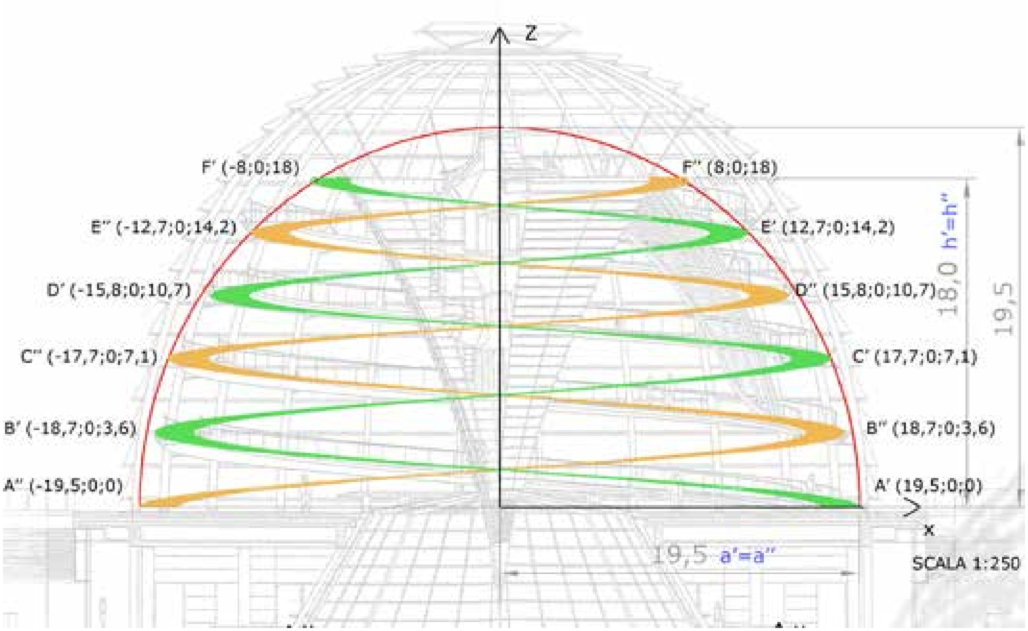

Figure 9
Reichstag dome - Norman Foster. Internal geometric singularity. Ramp as a spiral inscribed in the circumference (Loxodrome).

seems possible to anticipate that the sake for searching the shape singularity as an end in itself, that many recognize as a common issue in contemporary architectonic structures, it seems to be necessary, but not sufficient, to mark the urban environment with significant permanent signs that need to go through a further long term process of historical, cultural and even social interpretation and acceptance.

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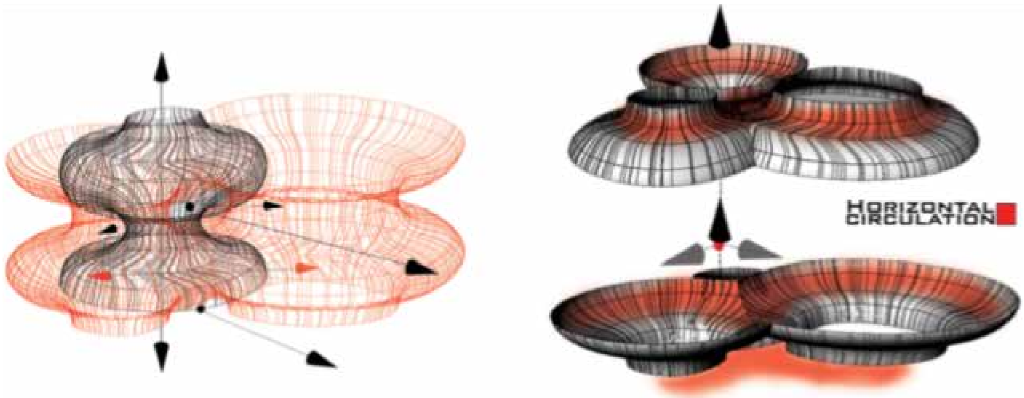

Figure 10
Taichung Metropolitan Opera House - Toyo Ito. Singularity in flux allowed by the walls which bends to merge with floors and ceilings.

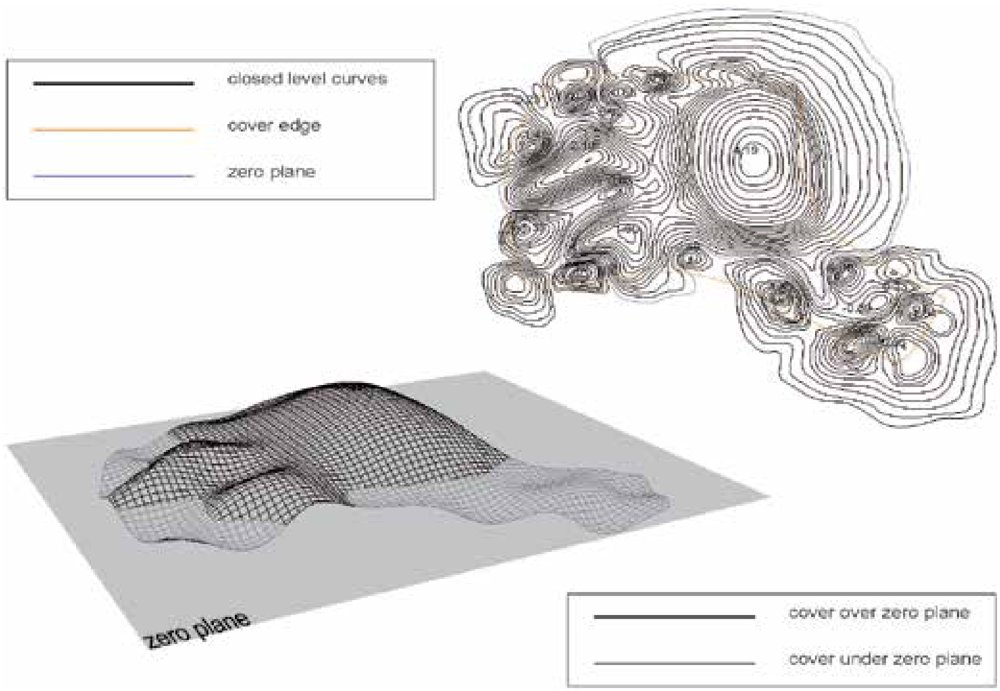

Figure 11
Meiso no Mori Crematorium - Toyo ito. A generative design applies the mechanichal thory that minimizes strain energy in a structure to create a rational free-cureved surface.

Figure 12
The organic shape of the "Bolla" (Bubble) designed by Renzo Piano on the roof of the Fiat Lingotto Factor in Turin.

Action Based Approach to Archaeological Reconstruction Projects: Case of the Karnak Temple in Egypt

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Abstract. *The proposed paper deals with a numerical approach that could better assist the archaeologist in the archaeological reconstruction projects. The goal of our research is to explore and study the use of computerized tools in archaeological reconstruction projects of monumental architecture in order to propose new ways in which such technology can be used.*
Keywords. *Architectural heritage; archaeological reconstruction; action-based modeling; architecture and complexity.*

INTRODUCTION

The definition and development of new modeling methods is the objective of a research project in progress at the CAD research group (GRCAO) of Université de Montréal. These methods aim for a better integration of the varying types of knowledge implicated in the reconstitution of ancient architectural structures, as well as greater flexibility in the manipulation and utilization of this knowledge. To reach this objective, technology will not suffice. It is necessary to integrate methods, knowledge and goals of a collection of scientific disciplines that are not used to working together (without forgetting the inherent incoherencies): to social sciences as with archeology (in the classical and not the anthropological sense of the term), history, art history, epigraphy and chronology, architecture, geometry, optics, and information technology must be joined. This requires that each discipline define itself in terms of what it can bring to the reconstitution of physical objects in an environment, and thus, the reconstitution of architectural heritage.

The case study: Karnak Temple

To do this, our project uses as laboratory the Karnak temples in Egypt: certain information is already available in the form of plans, surveys, elevations and sections of existing monuments (with or without proposed restitutions), and excavation reports, while other information is still to be surveyed on site, or catalogued. Beyond the technical aspects that allow for the precise encoding of the basic components of constructions and structures, the method allows for the elaboration of a reconstitution that notes the different proposed reconstitutions of parts that are either currently missing or have been modified several times over a millennium of history. Also the method takes into account the degree of probability of the proposed reconstitutions.

To experiment our general approach of restitution, we choose the case study of the VIIth pylon in the Karnak Temple. The choice of this case study follows directly from the data availability. Indeed, the seventh pylon was a pretext for testing survey func-

Figure 1
The VIIth pylon divided into as many blocks as it contains.

tions in the project "Karnak-1" in GRCAO. We made a division of the complete structure of our case study (the VIIth pylon in the Karnak Temple) in as many blocks as it contains (Figure 1). Our goal is to assign to each of the blocks from corpus, its place in the general scheme of the studied structure. It is a set of epigraphied blocks with variable dimension.

When the corpus of blocks to be processed is very important, it is necessary to find the necessary resources to divide the whole into "manipulable" units through a multitude of actions which identify the blocks that have one or more common characteristics. The data can be used to identify the relative position of a unit with respect to another. Based on the geometric attributes, iconographic or other, the goal is to identify, manipulate and / or to connect and recreate these attributes in order to find indices that will help us to argue one or more assumptions about the hypothetic position of a block in relation to the adjacent ones, respecting of course the overall assembling of the general unit.

The survey and description of blocks

Carrying out epigraphic surveys is a very important task in archaeology, particularly in Egyptology because all the monuments contain numerous texts and scenes engraved on their architectural elements. It is a matter of urgency to do such surveys, because the inscriptions are deteriorating at great speed and there is a real risk of losing completely some impotents scenes.

The main problem at the present time is that the traditional methods carried out to survey the inscriptions are very time-consuming. For example the most common of these methods consists in making facsimiles of the wall to be surveyed, with photographs as background or simply with transparent sheets placed against the surface of the wall. This method involves numerous checks during the drawing process and is therefore rather tedious, because it requires the collaboration between different drawers.

Research carried out by the GRCAO leads to present method of computerized epigraphic survey that can be used for drawing and recording the hieroglyphic signs for all planar, but also conical and cylindrical, architectural elements of Egyptian temples. This method is user-friendly for archaeologists and epigraphists alike, thanks to the very detailed menus created in the AutoCAD© software. Numerous choices are constantly available during the surveying process, and every operation can be undone if necessary. Each surveyed sign is recorded in a database, in the form of a text file, which can later be used for other research purposes: studies on the shapes of hieroglyphs, automatic translation of the texts, search for missing elements, etc. This method considers the needs of the epigraphists and offers them the possibility of controlling various operations during the computerized survey process. Particular emphasis has been put on the fact that the decoration of a monument is indissociable from its architectural support. The drawings must be recorded with all the information necessary to understand their real meaning (i.e. the architectural and archaeological context). The recording format has been normalized so as to be exploitable for research purposes (statistics, restoration of structures, etc.) (Figure 2).

Moreover, various exploitations (reconstitution, paleography, etc.) are possible, thanks to the fact that all the signs drawn are recorded in a universal format. The publication of the texts can still be made

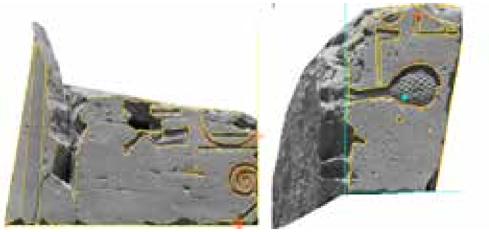

Figure 2
Survey of the blocks in the VIIth pylon using the GRCAO method.

in paper form, but can now be in numerical form too, which in turn leads to other possibilities such as data exchange. This approach is of course adaptable to the survey of other types of temples (Greek for example).

DEVELOPMENT AND VALIDATION OF OUR ARCHAEOLOGICAL RECONSTITUTION MODEL

This part presents an exploratory prototype developed to assist (but not to control) the reasoning and decision-making in the formulation and computer simulation of architectural reconstruction hypotheses. This "assistance" will be taking advantage of the knowledge and data available or extrapolated by the production of computer models as well as alphanumeric documents resulting from targeted questions of the databases.

The Use of ICT in archaeological reconstruction projects

In our quest to answer this question, we begin with a study of the different restitution approaches used in various phases of archaeological reconstruction projects. This involves understanding how the different methods of approach have evolved (epistemologically), how those involved in such projects have put information and communication technologies (ICT) to use in the field of built heritage. This study has identified two main avenues: one whose aim is the "representation" of project results and another whose aim is to model this process in order to assist the archaeologist through various phases of a project. It is the second approach that can better respond to our goals and that can guarantee to the archaeologists an effective utilization of the possibilities offered by computer-assisted tools. This study allowed us to demonstrate the complex and systemic nature of using ICT in the field of archaeological reconstruction. The multiple actors, conditions, means and goals considered in archaeological reconstruction projects have led us to explore a new approach that reflects this complexity.

Study of the publications in the archaeological projects

In order to achieve the goal of our research, it was necessary to further study the nature of the archaeological process. This involved understanding the links and interrelations between the various components that defines the archaeological approach and the various thought processes involved in archaeological reconstruction projects.

In summary, archaeologists perceive and describe their approaches through filters determined by their use of these descriptions. Any scientific description is both the result of past constructions, and the source of present and future constructs to enrich them or replace them. These filters can, in many cases, push the archaeologists to become very attached to their hypothesis and persist in not recognizing their weaknesses.

From this perspective, archaeological publications all look the same slightly "*there can not describe a monument without referring implicitly to the state of knowledge and research objectives that determine proper method the substance and form of the description, so that a catalog, especially when the terms "rational" is a theoretical construct in the same way if not to the same extent that any historical essay* " (Gardin, 1979). This study showed a direct relationship between the subjective nature of the process and the diversity of approaches and thought processes which can be implemented.

This exploratory and propositional research reinforces the systemic and complex nature of our approach and prompts us to explore, in practice and through published literature, the elements of known reality. The study of archaeological reasoning through academic publications has allowed us to propose an initial typology of arguments studied. Each of these typologies reflects a methodological approach based on organized actions that can be recorded in a set of reasoning modules. The classification of the various arguments by type of reasoning in order to determine the configuration of a building has enabled us to establish a model of the various components of the archaeological process as well as validation rules that have been used by archaeologist in real reconstruction projects.

This research has allowed us to highlight phenomena and observed processes, leading to a model representing interrelationships and interactions as well as the specific results of these complex interconnections. This pattern reflects a cyclical process of trial and error, in which the actors consecutively 'experience' (according to the project's goals and through reasoning modules), several answers to the questions exposed to him under the corpus definition, description, structure, interpretation and validation of the results until the latter would appear to meet the original targets. Three examples of reasoning modules have been developed and tested through a case study of the VIIth pylon of the Karnak temple in Egypt.

Geometric approach to restitution: Example of a module using the geometric reconstruction of 2D objects

Considering the large number of blocks that archaeologists handle in archaeological reconstruction project, it will be extremely difficult for them to visually identify formal and geometric complementarities among the studied blocks. The main goal of this module is to present a reasoning tool to search for possible complementarities among the geometric characteristics of the identified blocks. It can assist archaeologists to identify, among the huge mass of available data, a manipulable subsets based on their geometric characteristics (Figure 3). This reasoning module may bring, in this case, a considerable assistance.

Stone, the basic component of a wall, is made

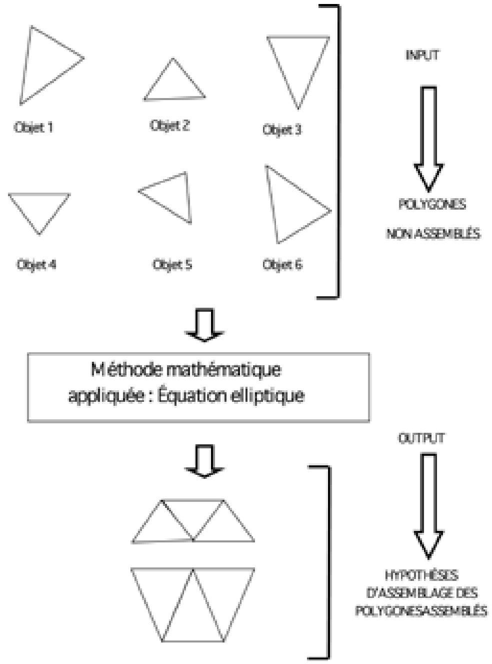

Figure 3
Operating principle to search for blocks assembly using the elliptical mathematical method.

up of lines and surfaces defining the boundaries of those faces of points and defining the ends of these lines. These data are essential for encoding neighborly relations between blocks because they are the main reliable parameters of adjacencies. Each block is individually registered using the survey method adopted (GRCAO method), in two ways:

- The outline of the blocks: this corresponds to the detailed record of the actual boundaries of the block witch will be saved as control points.
- The min-max block: this corresponds to the polygon including the useful surface of the studied block. This contour is stored as control points coordinates.

Although this reasoning module is based on complex mathematical models, the user will not, in any case to manipulate them. All calculations will be back plans and the user will have to handle only 'objects', which he is used to deal with. We have demonstrated, through the exploration of a 2D topological help reclaim the blocks, the relevance of such an approach and the relative facility on the computer translation of the actions that may include the reasoning module. This module, and meeting our original goals, open to the implementation of other actions (respecting the same logic). Depending on the initial objectives and methods that archaeologists adopt, a specialized team that will be responsible for translating actions that he wishes to undertake and thus to optimize the contribution that can bring computer tools in the success of the architectural reconstruction projects.

Iconographic approach to restitution

More than any other civilization, the ancient Egyptians have associated iconography and epigraphy to architecture. Indeed, the temple walls are covered with inscriptions and bas-reliefs whose theme, which meets to a large extent to known conventions, is the basis for the restitution of significant architectural parts of the temple.

Schwaller de Lubicz (1999) introduced a technique that allows the study of the key of reading scenes through the disposal of their constitutive iconographic elements. It is to identify the different modes of expression of what he defined as "an iconographic language", that when combined together, can give an early sense of the studied scenes. The three modes of expression used by this language are:

- Figurative language: it is a language that can cover all the iconographic elements that belong to different known elements and their associated scenes.
- The processes of arrangement: Addition and supervision of iconographic elements.
- Figures of style: It is to identify the language of the image through reading and decrypting formal and subtle arrangements that the Egyptians invented.

These complex arrangements are governed by mathematical principles that affect the structure of the scene. One approach will be to take advantage of these rules of composition through the implementation of the correspondent reasoning module. This will be our first approach.

Another very important consideration in the overall structure and composition of a scene element: the "continuity of the theme." Indeed, each of the blocks that make up the structure includes a portion of the overall scene. Our second approach will be to consider a scene as an assemblage of iconographic elements. These elements, taken together, could possibly give a meaning to the whole (register, wall, room, etc.). It is therefore to study the type of continuity and propose a reasoning module that can assist archaeologists in this type of work.

First approach: Metrological aspects in the Egyptian iconography

Our introduction to this metric aspects of Egyptian iconography is based primarily on the work of Robins et al. (1994), Donovan (1986) and Carlotti (1995). Egyptian architects built their monuments by following rules that respected the standards of proportion generally defined by type of building space, whether courses, pylons or columns (Carlotti, 1995). Restoring a monument according to length units commonly used in Pharaonic Egypt, using sometimes the digital measurement system (for architecture) uncial (the decor on the walls), proves a worthy track looking to be explored. Iconographic representations on the walls of temples do not escape this rule and follow a so-called "The Last Tile" technique based on the canons of proportions. Indeed, measurements of different parts of an Egyptian artwork, especially the wall decorations, were set one with respect to the other in a precise and rigorous way. This "Canon" was based on the proportions of the human body. Modern reconstruction of this canon of proportions is mainly based on the study of the guidelines partially preserved on the walls and statues. The data, the units of measurement as well as the rules of their use by Egyptian artists are still controversial.

For our case study, we have based our approach on the work of Carlotti (1995) to establish the proportion module used in the VIIth pylon at Karnak. Depending on the construction period, we may

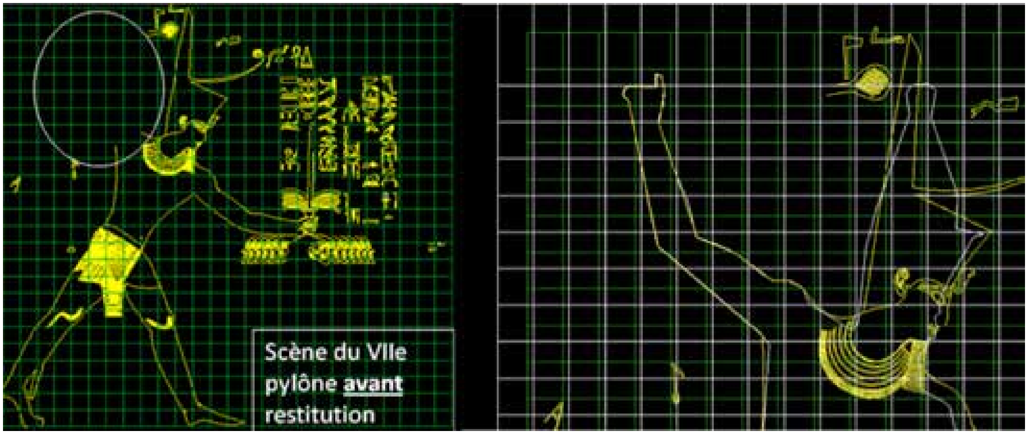

Figure 4
Restituation of the VIIth pylone scene using the iconographic module.

have an approximate value of the module used in the scene that appears on the “Medinet Habu” pylon. The iconographic analysis of the pylon reveals a traditional theme that represents the scene of the “massacre of the enemies”. This scene was repeated in several Pharaonic structures. In an approach for a restitution by completion, and based on the complete scene on the temple pylon “Medinet Habu”, our goal is to determine the missing elements, and so complete the scene studied (Figure 4). This treatment was made in four steps:

- Step 1: Determination of the modulus value proportion of the VIIth pylon at the Karnak temple,
- Step 2: survey of the representation of the Pharaon on “Medinet Habu temple” and on the VIIth pylon with the GRCAO method,
- Step 3: Making the superposition of the 2 surveys after practicing the technique of “tiles making”,
- Step 4: Completing the missing part of the scene (Figure 5).

Second approach: Typology and iconographic connections

To study the iconographic continuity, we conducted an analysis of vicinity of each of the connections between the blocks that make up the VIIth pylon. Our goal is to study their type and their variants. Our analysis allowed us to identify eight types of continuities between the studied blocks :

- linear continuity
- Iconographic continuity: human body, hieroglyphic sign, other
- relief continuity: Level Difference, Surface Uncoupling
- Continuity of the type of engraving: texture continuity, etc,
- Text continuity
- Geometric continuity: same Min-max, etc.
- Theme continuity: Text, cartouche, human, etc
- Zone continuity: horizontal or vertical text, etc.

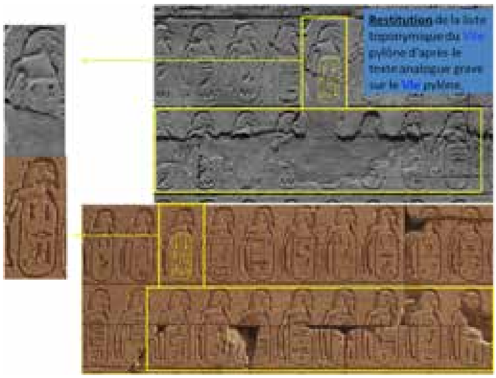

Figure 5
Restitution of the toponimic list of the VII^th^ pylon according to the similar text engraved on the VI^th^ pylon.

Figure 6
Blocks assembled using the typology and iconographic connections.

Other elements of description can be added according to the competence of the actor and the degree of precision considered. Actors must not to describe the block as an overall unit, but exploded into as many constituent elements. That is to say, it must offer the user the opportunity to indicate areas of vertical text, horizontal text areas, friezes, human body, etc. A module based reasoning approach can provide the archaeologist additional tools to search, for example, all the text boxes with a width x or an additional sign truncated, etc.. This module is based on features to combine iconographic themes geometric aspects of signs and symbols. It is a tool to assist players in the field in studies of possible connections between the blocks to reconstruct.

The general topology of the block is defined in a data structure based on the control points where we can find the points that define the edges of the block which themselves define the surveyed surface. The direction of the view can also be defined (based on control points, too) in order to give meaning to the “left” expression, “right”, “up” and “down” (eg the scene). All objects must be observed on the same side.

Attributes faces statements therefore represent qualitative information such as their orientation in the scene, exposure direction (smooth and treated when it is visible to spectators and untreated when it is not visible). It can also be determined by the inscriptions and it carries this on two levels: iconography (the figures, ornaments and inscriptions) and semantics (the interpretation and understanding of the iconographic elements) (Figure 6).

CONCLUSION

This experiment allowed us to confirm the overall appearance and total interdependence between the different components and activities of the archaeological approach in the archaeological restoration projects. On one hand, the procedure used to identify and describe the artifacts has a direct impact on the possibilities of data operations implemented. On the other hand, the goals of the actors and the nature of reasoning implemented determine the types of data to be recorded and the degree of interpretation to be made.

The results show that the reasoning modules offer an interesting solution to assist archaeologists in theses projects. The multiple action combinations offered by theses modules are an advantage to many approaches and thought processes which could be useful to such projects while maintaining the progressive nature of the overall system.

The type of goals of our project has greatly influenced the course of all operations related to the choice of corpus, to their description, to their structure, their interpretation and the validation of the results we had. Indeed, the survey methods and data structures have been chosen according to the nature of our corpus (pictures recovered) as well as “inputs” and “outputs” on the reasoning modules that we developed . The choice of data, the way to see them, how to classify them and how to comment them were determined with reference to the purpose of our construction: restoring the blocks of the VIIth pylon (Figure 7).

Our model expresses not the way has been built construction, but its logical architecture, once completed. Indeed, the results presented, through our case study, have shown that the approach is often an iterative process that is constantly progressing (by trial and error) through the manipulation of data by actions encapsulated in various modules of reasoning (order of epigraphic (text and phonetic), constructive order, physical or geometric, etc..). In this progression, we have "experienced" various hypotheses through the application or implementation of new reasoning modules reasoning. The finding of inadequacy determined each iteration and pushed us back to the data and the means available to a new definition of corpus, description, structure or interpretation. It was mainly to combine several reasonings to reduce the number of available possibilities and progress until the results can meet the objectives of the study. The evolutionary aspect of the system allows us to add other modules of reasoning if the resources available cannot enable the objectives of the actors.

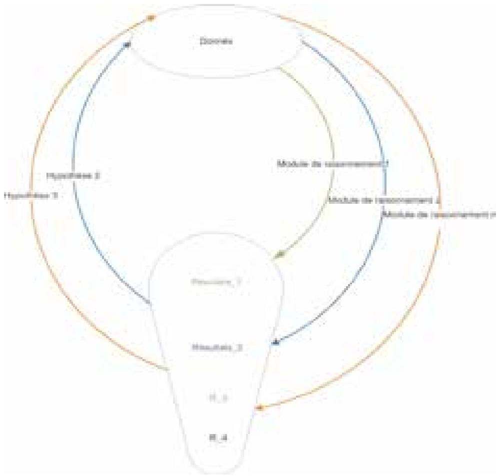

Figure 7
Model of archaeological reconstruction using the reasoning modules.

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Models of Computation: Human Factors

Fusion of Perceptions in Architectural Design

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Abstract. *A method for fusion of perceptions is presented. It is based on probabilistic treatment of perception, where perception quantifies the chance an unbiased observer sees an environmental object, and the associated probability can be interpreted as degree of awareness for the object. The approach uniquely accounts for the fact that final realization or remembrance of a scene in the brain may be absent or elusive, so that it is subject to probabilistic considerations. For objects that are to be perceived from multiple viewpoints, such as a sculpture in a museum, or a building in its urban context, the probabilistic approach uniquely defines the fusion of perceptions. This is accomplished by carrying out the probabilistic union of events. The computation is presented together with its geometric implications, which become rather intricate for multiple observers, whereas the computation is straight forward. The method is exemplified for two applications in architectural design at different scales, namely interior and urban design, indicating the generic nature as well as the large application potential of the method.*
Keywords. *Perception; vision modeling; architectural design; evolutionary search.*

INTRODUCTION

Perception, and in particular visual perception, is an interdisciplinary concept taking an important place in many diverse applications. These range from design of objects and spaces, for which perceptual qualities are aimed (Bittermann and Ciftcioglu, 2008), to robotics where a robot moves based on perception (Ciftcioglu et al., 2006a; Bülthoff et al., 2007). However, although visual perception has been subject to scientific study for over a century, e.g. see Wertheim (1894), it is interesting to note that it remained mysterious what perception precisely is about, while it eluded mathematical modeling until very recently. Many approaches to perception, in particular in the domain of psychology and neuroscience, are based on experiment, while underlying theoretical models or hypotheses are either simplistic, ambiguous or even absent (Treisman and Gelade, 1980; O'Regan et al., 2000; Treisman, 2006), so that gaining insight into the nature of human perception from the experiments remains minimal. However, considering that the perception phenomenon is due to brain processing of retinal photon-reception, it should be clearly noted that the phenomenon is highly complex. That is, the same experimenter may have different perceptions of the same environment at different times, depending on the complexity of the environment, psychological state, personal preferences and so on, not to mention different vantage points. Due to the complexity of the brain processes and diversity of environments subject to visual perception, the empiric approaches to perception yielded merely rudimentary understanding of what perception is. Although some verbal definitions of the concept are presented in the literature, e.g. (Gibson, 1986; Palmer, 1999; Foster, 2000; Smith, 2001) due to excessive ambiguity of the linguistic expressions, these are not to be converted to precise or even more unambiguous mathematical expressions.

Computational approaches addressing some perception aspects have been proposed by Marr (Marr, 1982) whose prescription is to build computational theories for perceptual problems before modeling the processes which implement the theories. Explicitly, different visual cues are computed in separate modules and thereafter only weakly interact with each other, where each module separately estimates scene properties, such as depth and surface orientation, and then the results are combined in some way. These works can be termed as image processing based approaches, and they are deterministic in nature, starting from simulation of retinal data acquisition. The retinal photon-reception certainly is the first stage in the time sequence of the processing in the visual system, and it might be dealt with by means of an image specified as a two-dimensional matrix. However, the ensuing neural processes are highly complex, so that retinal image does not imply that all the information in the scene is registered in the human brain and remembered shortly afterwards. Only part of the visual information is remembered. For instance, it is a common experience that when we look at a scene, we are not aware of the existence of all objects the scene comprises. This is easily verified for scenes where the number of objects exceeds about seven objects.

In this work a probabilistic approach is adopted for perception, where perception is considered a whole process from the stimulus coming from the scene to mental realization in the brain. In other words, all complex processes, e.g. image formation on the retina, processes in the visual cortex in the brain, and final realization of 'seeing' is modeled as a single probabilistic event, where 'seeing' in that probabilistic description is considered to be perception, where remembrance is a matter of probability. The final realization or remembrance of the scene in the brain may be absent or elusive, which is subject to probabilistic considerations. This approach has been described and its validity demonstrated (Ciftcioglu et al., 2006b; Bittermann and Ciftcioglu, 2008).

This probabilistic approach is unique in the sense that the perception refers to human perception. In the field of computer vision perception is considered to be a mere image processing and ensuing pattern recognition process, where Bayesian methods are appropriate (Knill et al., 2008; Knill and Richards, 2008; Yuille and Bulthoff, 2008). Bayesian approach is to characterize the information about the world contained in an image as a probability distribution which characterizes the relative likelihoods of a viewed scene being in different states, given the available image data. The conditional probability distribution is determined in part by the image formation process, including the nature of the noise added in the image coding process, and in part by the statistical structure of the world. The Bayes's rule provides the mechanism for combining these two factors into a final calculation of the posterior distribution. This approach is based on Bayes formula

$$p(s\,|\,i) = \frac{p(i\,|\,s)\,p(s)}{p(i)} \qquad (1)$$

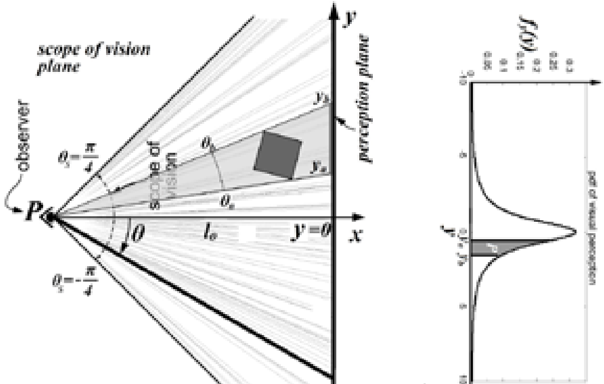
Here *s* represents the visual scene, the shape and location of the viewed objects, and *i* represents the retinal image. *p(i|s)* is the likelihood function for the scene and it specifies the probability of obtaining image *i* from a given scene *s*. *p(s)* is the prior distribution which specifies the relative probability of different scenes occurring in the world, and formally expresses the prior assumptions about the scene structure including the geometry, the lighting and the material properties. *p(i)* can be derived from *p(i|s)* and *p(s)* by elementary probability theory. Namely

$$p(i) = p(i\,|\,s)\,p(s) + p(i\,|\,\bar{s})\,p(\bar{s}) \qquad (2)$$

so that (1) becomes

$$p(s\,|\,i) = \frac{p(i\,|\,s)\,p(s)}{p(i\,|\,s)\,p(s) + p(i\,|\,\bar{s})\,p(\bar{s})} \qquad (3)$$

The posterior distribution *p(s|i)* is a function giving the probability of the scene being *s* if the observed image is *i*. Bayesian approach is appropriate for



(a) (b)

Figure 1
Plan view of the basic geometric situation of perception; P represents an observer's point, viewing an object (a); probability density function characterizing perception along y direction for $l_o=2$ (b).

computer vision, because for human *p(i|s)* is almost clearly known, that is *p(i|s)*=1. Consequently, $p(i|\bar{s})=0$ and from equation (3)

$$p(s \mid i) = \frac{1 \times p(s)}{1 \times p(s) + 0 \times p(\bar{s})} = 1 \qquad (4)$$

which is independent of the probabilistic uncertainties about the scene. This means, as the *p(i|s)* is definitive for human recognizing a scene, *p(s|i)* is also definitive, being independent of *p(s)* which is the prior assumptions about the scene structure including the geometry, the lighting and the material properties. The effectiveness of Bayes for machine vision is due to its recursive form, providing improved estimation as the incoming information is sustained.

The organization of the paper is as follows. In the *modeling human perception* section a vision model is established. In the *perception from multiple viewing positions* section, the fusion of perceptions from multiple viewpoints is derived. In the section *experiments,* two experiments demonstrating the fusion of perceptions in architectural design are presented, and this section is followed by *conclusions*.

MODELLING HUMAN PERCEPTION

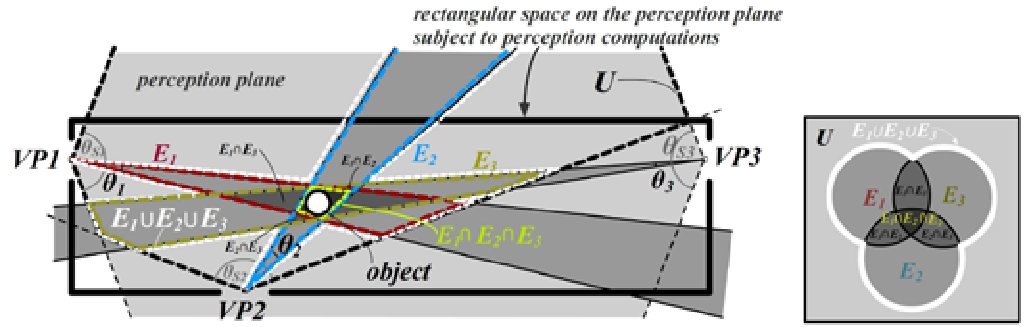
In the human perception an object is visually seen, but its remembrance is subject to some degree via probabilistic considerations. This is described elsewhere (Ciftcioglu et al., 2006b; Bittermann and Ciftcioglu, 2008) and briefly mentioned as follows. We consider a basic geometric situation as shown in Figure 1a. For a visual scope $-\pi/4 \leq \theta \leq \pi/4$ the probability density characterizing perception along the *y*-direction is shown in Figure 1b for $l_o=2$ and given by

$$f_y(y) = \frac{2}{\pi} \frac{l_o}{(l_o^2 + y^2)} \quad (-l_o \leq y \leq +l_o) \qquad (5)$$

The probability density with respect to *q* is given by $f_\theta(\theta)=1/\theta_S$, where $\theta_S=\pi/2$. The one-dimensional perception of an object spanning from arbitrary object boundaries *a* and *b* on the *y*-axis is obtained by

$$P_y = \int_{ya}^{yb} f_y(y)\, dy \qquad (6)$$

yielding perception as an event being subject to probabilistic computation. For the case of perception of an object by a single human observer the computation is accomplished always by (6) when the projection of the object is considered as one-dimensional along a line. The same computation can be valid for three-dimensional objects, provided we consider the projection of the object on a plane. In this case, the same formulation can be used twice for each respective orthogonal dimension of the plane in the form of product of the two probability densities integrated over the projected area on the plane.



(a) (b)

Figure 2
Perception events E_1, E_2, and E_3 respectively denoting perception of an object from three viewpoints VP_1, VP_2, VP_3; the union of the events is indicated by the white dashed line (a); Venn diagram corresponding to the perception events in Figure 2a (b).

PERCEPTION FROM MULTIPLE VIEWING POSITIONS

In many occasions an object is subject to perception from multiple viewing positions, either by the same observer or by multiple observers. That is, perceptions from different viewing positions are subject to fusion. As the perception is expressed in probabilistic terms, the union of different perception events is subject to probabilistic computation. Requirements with respect to perception from multiple viewing positions can occur in many practical applications. To demonstrate fusion of perceptions we restrict the study to two basic examples. It is noted that they may not be important depending on the particular design problem; however the examples are simple in order to clearly explain the method. The same method can be applied in more complex tasks, such as courtroom design (Bhatt et al., 2011), auditorium design, office design, as well as urban design. In the first case study we consider an exhibition gallery environment, where there are several entrances to a gallery space, and we are wondering what the best position to place an object is, so that perception of the object is maximized. In the second application we are considering an urban environment, where a building will be erected that will be seen from a number of prominent viewing positions. We are interested to obtain the perception of the different parts of the future building as fusion of perceptions from these viewing positions. In the latter case study this is to identify which part of the building is most conspicuous, in order to determine for instance the building entrance that should preferably be positioned. Consequently it will be easily noticed.

A scene subject to investigation as exemplary case is shown in Figure 2a, with the three perception events E_1, E_2, and E_3. The figure shows a plan view of the space and the location of an object subject to perception assessment and optimal positioning. The object is subject to perception from the three viewing positions VP_1, VP_2, and VP_3, where it respectively subtends the angle domains θ_1, θ_2, and θ_3 as seen in the figure. The dashed lines in the figure indicate the boundaries of the observer's visual scope at the respective viewing positions spanning the angles θ_{S1}, θ_{S2}, and θ_{S3}. Figure 2b shows a Venn diagram corresponding to the perception situation in Figure 2a. In the case of perceiving an object from several viewing positions this corresponds to the probabilistic union of the perceptions, which is obtained by $P(E_1 \cup E_2 \cup E_3)=P(E_1)+P(E_2)+P(E_3)-P(E_1 \cap E_2)-P(E_1 \cap E_3)-P(E_2 \cap E_3)+P(E_1 \cap E_2 \cap E_3)$, as this is seen from Figure 2b. It is noted that the events $P(E_1)$, $P(E_2)$, and $P(E_3)$ are independent. In the three dimensional perception case θ_1, θ_2, and θ_3 become solid angles Ω_1, Ω_2, and Ω_3 and the scopes θ_{S1}, θ_{S2}, and θ_{S3} become solid angles Ω_{S1}, Ω_{S2}, and Ω_{S3}.

EXPERIMENTS

Computer experiments are carried out, where $P(E_1)$, $P(E_2)$, and $P(E_3)$ are obtained by probabilistic ray tracing, so that a three-dimensional object is subject to perception measurement without need for projection to a plane as shown in Figure 1a. That is, the solid perception angle Ω subtended by the object, as well as the solid angle Ω_S, which defines the observer's visual scope, are simulated by vision rays that are sent in random directions within the three dimensional visual scope. The randomness in terms of unit Ω is characterized by $f_\Omega(\Omega)=1/\Omega_S$, conforming to the uniform pdf $f_\theta(\theta)=1/\theta_S$ that models the unbiased observer in the case of perception of an object that is contained in the scope of vision plane, as seen in Figure 1a. In the experiments the number of vision rays is denoted by n_v. An object within the visual scope will be hit by a number of vision rays n_p, and these rays are termed perception rays. The perception of the object is given by $P=n_p/n_v$.

Experiment Nr. 1

The first experiment concerns a basic issue in an architectural design, namely positioning an object, so that its perception from several viewing positions is maximized in the sense that the object will be perceived well at least from one of the relevant viewpoints. This issue is exemplified by means of positioning a sculpture in a museum space having several entrances; namely the space has three doors, where the relevant viewing positions are located denoted by VP_1, VP_2, and VP_3. The problem is to position the sculpture in the space, so that the visitors entering the space from either door will notice the object. The problem is to maximize the union of the perceptions from the three viewpoints $P(E_1 \cup E_2 \cup E_3)$, while at the same time the sculpture positioned at point x should not obstruct entrance to the room from either door. The latter constraint is formulated by the condition $\|x-x_o\| \geq 3$, where x_o is the position of each viewing position. The maximization is carried out by the method of random search, accomplished through the method of genetic algorithm. Genetic algorithm is a stochastic optimization method from the domain of computational intelligence. The algorithm starts from a number of random solutions referred to as members of a population. Each member satisfies the objective function to some degree, which is termed fitness. In the algorithm population members with a comparatively high fitness will be favored over solutions with low fitness, by giving the former a higher chance to remain in the population and to produce new solutions by combining fit solutions. The combination among solutions is referred to as crossover operation, and it is carried out among pairs of population members referred to as parents. Crossover entails that the parameters constituting a parent are treated as binary strings, and portions of the strings are exchanged among the two solutions to create new solutions with features from both parents. This process is repeated for several iterations, and due to the probabilistic favoring of fit solutions, eventually optimal solutions appear in the population (Goldberg, 1989; Zalzala and Fleming, 1997).

The resulting best solution after 40 generations is shown in Figure 3a in a plan view and in Figure 3b in perspective view, where the perception rays are seen. The circles in the figures mark the boundaries at 3.0 m distance from the doors. In Figure 3c-e the space is shown from the respective viewing position VP_1, VP_2, and VP_3. The best position of the sculpture is at the edge of the circle in front of viewing position VP_1. This position has the highest union of perceptions in the feasible region, namely P_U=.307. This is composed of the perceptions P_1=.157 at VP_1, P_2=.063 at VP_2, and P_3=.048 at VP_3.

For comparison the second best position is shown in Figure 4, namely the perceptive plan view in Figure 4a, perspective perceptive view in Figure 4b, and the perceptive views from VP_1, VP_2, and VP_3 in Figure 4c-e respectively. The union of the perceptions P_U=.255, that is 17% lower compared to the best solution in Figure 3. The union is composed of the perceptions P_1=.072 at VP_1, P_2=.152 at VP_2, and P_3=.033 at VP_3. The results demonstrate a common design knowledge, namely when one aims to maximize the perception of an object in a space with several possible viewing positions, it is preferable to position the object to have a high perception for at least one of the possible positions, for that matter VP_1, rather than having several moderate percep-

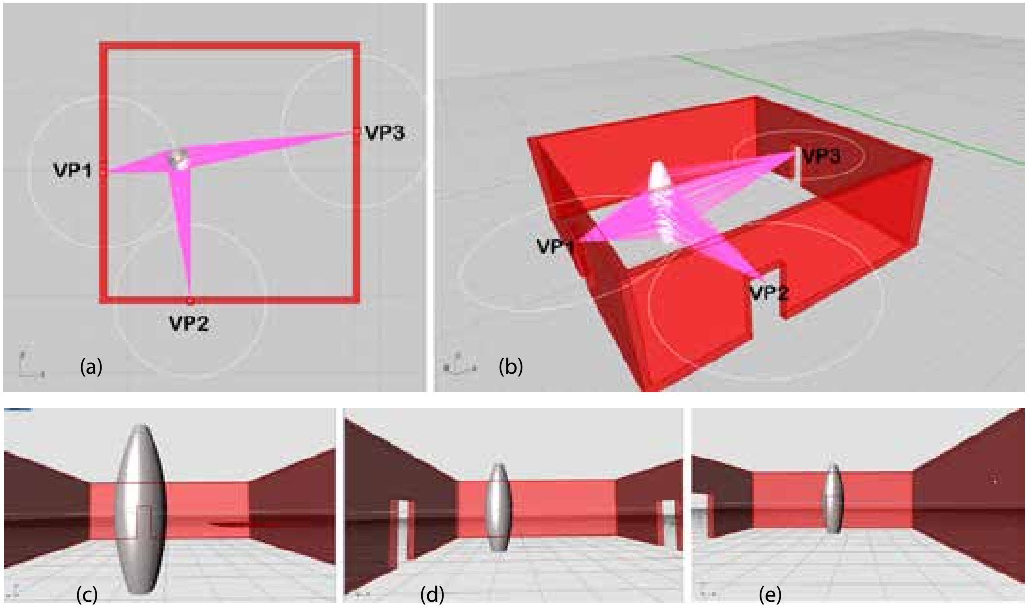


Figure 3
Best position for the sculpture in a plan view (a); in a perceptive view (b); for VP_1, P_1=.157 (c); for VP_2, P_2=.063 (d); for VP_3, P_3=.048 (e).

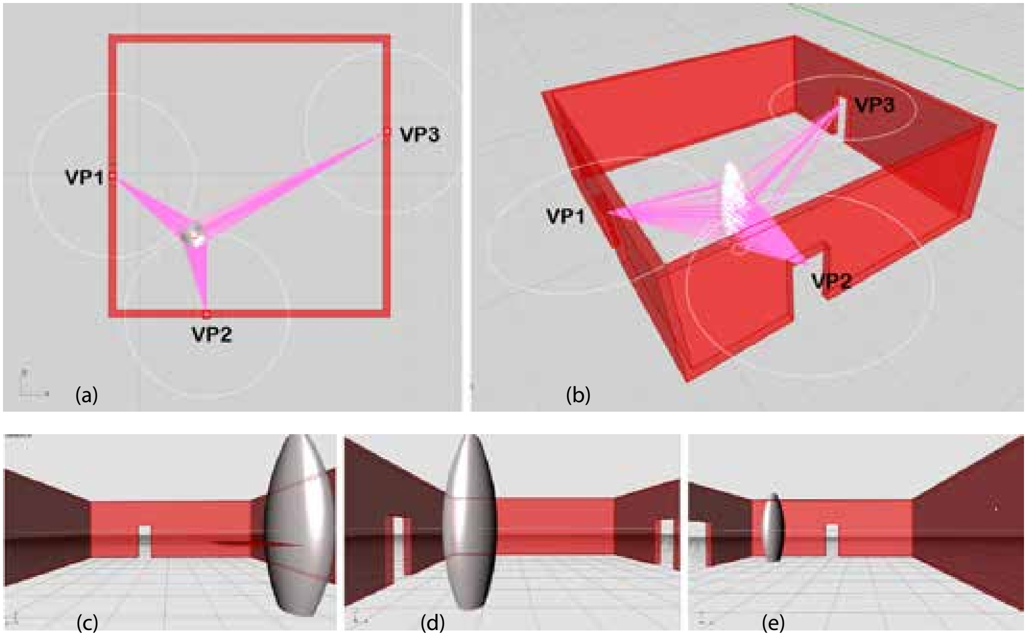


Figure 4
Second best position for the sculpture in a plan view (a); in a perceptive view (b); for VP_1, P_1=.072 (c); forVP_2, P_2=.152 (d); for VP_3, P_3=.033 (e).

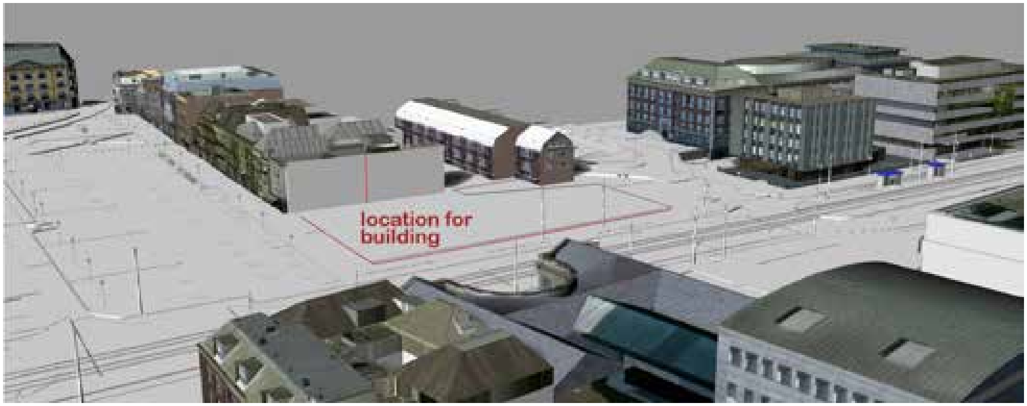


Figure 5
Location in an urban scene, where a new building is subject to perception considerations.

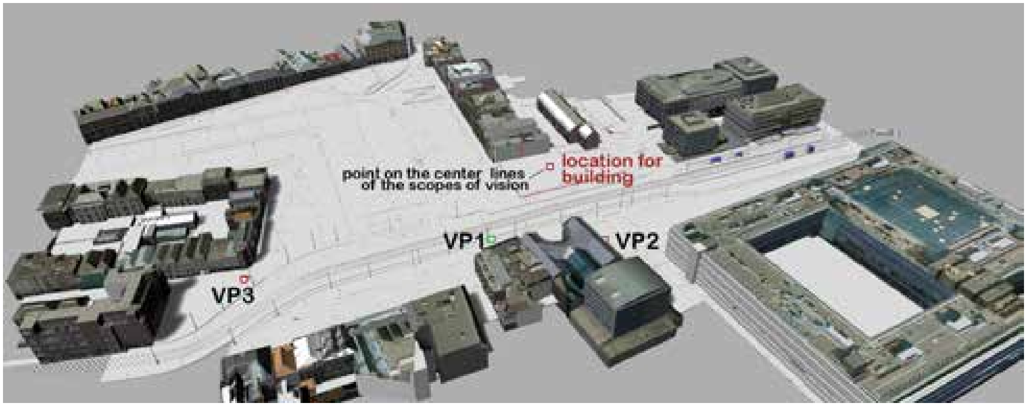


Figure 6
Zoomed out rendering of the urban scene in Figure 5, where a new building is subject to perception considerations from three viewpoints.

tions, i.e. without any outstandingly high one. The lower perceptions in Figure 4c demonstrate the implications of the Cauchy function in Figure 1b, where deviation from the frontal direction for an object, in particular at a near distance from the observer, yield reduction in probability density, i.e. visual attention is diminished in this case.

Experiment Nr. 2

A second experiment concerns the perception of a building in an urban context from three viewpoints that are prominent locations in the surrounding of the building. The location in an urban scene, where a new building is subject to perception considerations, is seen in Figure 5. The zoomed out rendering of the scene in Figure 5 is shown in Figure 6, where the three viewing positions VP_1, VP_2, and VP_3 are indicated. Figure 7 schematically shows the floor plan of the urban situation, as well as the perception cones and vision scopes belonging to the viewing positions, which are the endpoints of streets entering to a square where the building is located. Figure 7b shows random vision rays having uniform pdf with respect to the vision angle modeling visual scopes for three viewing positions. Figure 7c shows those rays among the vision rays that hit the building subject to perception, for perception computation. The results from the perception fusion for the respective building envelope portions are shown Figure 8, where the numbers display the fused perception associated with the respective portion. From the analysis it is seen that the part of the envelope that is most intensely perceived from the three viewpoints, is the area in front of VP_2, while the second most intense part is the part of the building corner oriented towards VP_1, which is expected considering the influence of the distance l_o in the perception computations in (5). The information obtained from perception fusion is of relevance for a designer determining formal and functional details of the envelope, for instance determining the position of entrance during conceptual design. Figure 9 shows the fused perceptions of the building envelope from the three viewpoints per envelope element with a vision scope that is 20% narrower compared to Figure 8.

CONCLUSIONS

A method for fusion of perceptions is presented and demonstrated with two examples from architectural design. The probabilistic treatment, where perception quantifies the chance that an unbiased observer notices an environmental object, is accomplished through fusion of perceptions. The method of quantified union of perceptions has been an unresolved issue up till now, that is resolved in this presentation. The fusion by probabilistic union yields significant information for designers. With the presented approach an object is to be perceived from several viewpoints at the same time. Such abstraction is necessary, since the precise analysis of the perceptions is a formidable issue due to abundant visual scene information. The use of perception fusion as constrained design objective has been demonstrated by coupling the method with a probabilistic evolutionary algorithm performing the constraint optimization. The combination of the two probabilistic methods is a powerful tool for designers as it permits treatment of architectural design to be highly constrained and involving many perception related demands. Although the examples presented are rather basic, the method is generic and yields highly appreciable scoring executions in diverse ap-

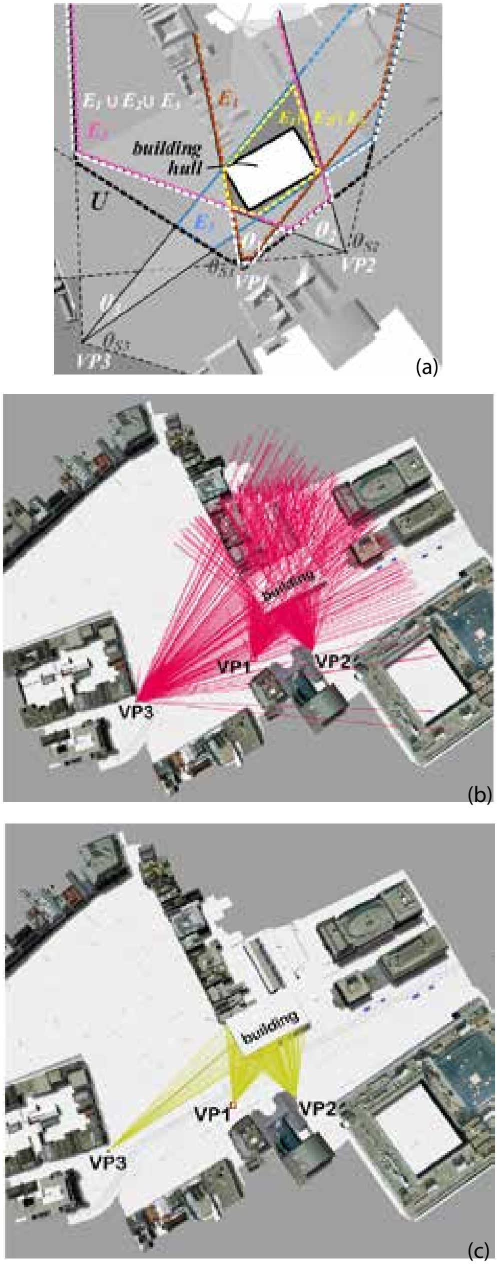


Figure 7
Scheme of an urban situation, where a building is subject to perception analysis from three viewpoints in plan view (a); random vision rays with uniform pdf w.r.t. the vision angle modeling visual scopes for three viewing positions VP_1, VP_2, and VP_3 (b); the rays among the vision rays that hit the building subject to perception (c).

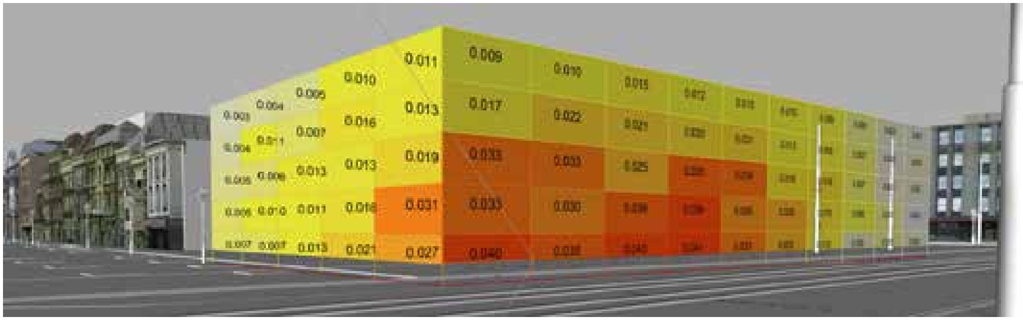


Figure 8
Fused perceptions of the building envelope from the three viewpoints per envelope element.

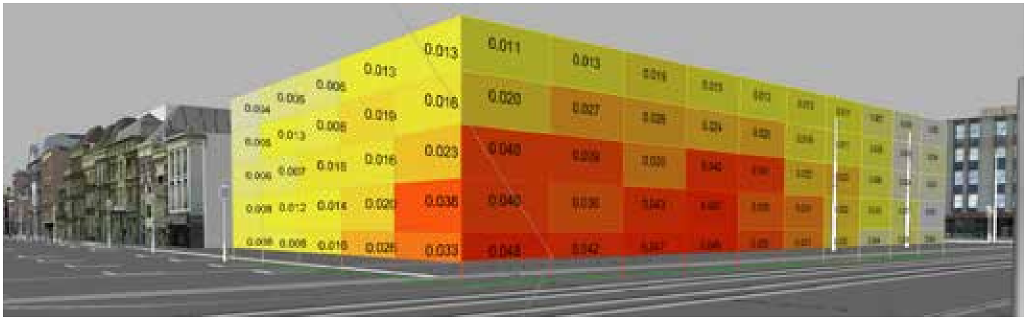


Figure 9
Fused perceptions of the building envelope from the three viewpoints per envelope element with a vision scope that is 20% narrower compared to Figure 8.

plications in the areas where perception plays a role, such as architecture, urbanism, interior and industrial design, as well as robotics.

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Ambient Surveillance by Probabilistic-Possibilistic Perception

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Abstract. *A method for quantifying ambient surveillance is presented, which is based on probabilistic-possibilistic perception. The human surveillance of a scene through observing camera sensed images on a monitor is modeled in three steps. First immersion of the observer is simulated by modeling perception of the scene from the camera locations using probabilistic perception approach. The perceptions are thereafter combined by means of probabilistic union, simulating simultaneous watching of the scene from multiple viewing positions. As third step the combined perceptions are converted to a possibility using triangular possibility density function. The latter step accounts for the fact that surveillance takes place via monitor depiction and not directly as perception of the actual physical scene. The method is described and demonstrated by means of an ambient surveillance application involving three cameras. The resulting possibility of perception is compared to the case of using two cameras, quantifying the added value of additional camera as to surveillance.*
Keywords. *Perception; possibility; ambient intelligence; surveillance.*

INTRODUCTION

Ambient Intelligence refers to electronic environments that are sensitive and responsive to the presence of people (Aarts and Encarnacao, 2006). Such electronic environments are called as ambient environment, referring to the surveillance of a physical ambience in the computer screen environment. Ambient Intelligence involves different fields including electrical engineering, computer science, industrial design, human machine interaction, and cognitive sciences. It stems from the combination of the three concepts ubiquitous computing, ubiquitous communication, and intelligent user friendly interfaces. It is considered to provide a vision of the information society, where greater user-friendliness, more efficient services support, user-empowerment, and support for human interactions is aimed for. In this vision people are surrounded by intelligent intuitive interfaces that are embedded in different kinds of objects yielding an environment that is capable of recognizing and responding to the presence of different individuals in a seamless, unobtrusive or invisible way (Ducatel et al., 2001). The European Commission's Information Society Technologies Advisory Group (ISTAG) considers Ambient Intelligence an important concept, as they predict that the concept will be applied to everyday objects such as furniture, clothes, vehicles, roads and smart materials. According to ISTAG, Ambient Intelligence implies machine awareness of the specific characteristics of human presence and personalities, taking care of

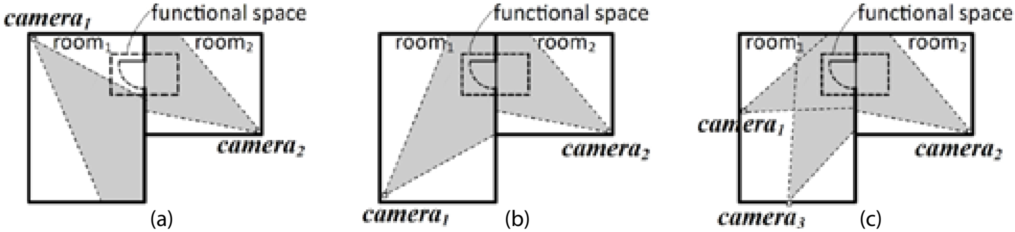

Figure 1
A door's functional space is not fully encompassed by the field of view of two cameras (a) (Bhatt et al., 2009); the functional space is fully encompassed by the field of view of two cameras (b); the space is fully encompassed by the field of view of three cameras (c).

needs and being capable of responding intelligently to spoken or gestured indications of desire (Weyrich, 1999). Benefits in some practical applications have been reported, see e.g. Augusto and Shapiro (2007), Streiz et al. (2007), Ramos et al. (2008), Augusto and Nugent (2006). Examples of application areas are personal assistance by mobile devices (Richard and Yamada, 2007), clothing (Boronowsky et al., 2006), entertainment (Saini et al., 2005; Dornbush et al., 2007), office and meetings rooms (Waibel et al., 2010), and home environments (Aarts and Diederiks, 2007; Nakashima, 2007). The benefits in the applications concern enhanced security, and utility. Concerning security, an issue of common relevance is surveillance of objects in buildings, e.g. see (Takemura and Ishiguro, 2010). The objects may concern building elements such as doors, hallways, etc., as well as valuable articles. For instance, in an environment the monitoring of people passing through the doors may be of relevance for security purposes, so that the locations where surveillance cameras are suitably placed, and the number of cameras used to supervise the environment, are important issues to consider. This may be relevant both during the design of an ambient environment, as well as during the assessment of the surveillance provided for an existing environment. In an existing work this issue is addressed by verifying if a functional space of a door is fully covered by supervision cameras (Bhatt et al., 2009), which is a requirement to guard the traffic between the rooms. This is seen in a plan view in Figure 1a, where the door and its functional space, which is shown by a rectangle, are not fully covered by the fields of view of two cameras. This yields requirement inconsistency. Figure 1b shows a situation where the door and its functional space are entirely within the fields of view of the two cameras, thereby complying with the requirement. In Figure 1c three cameras are used, and the consistency requirement is also fulfilled.

In an ambient intelligent system, human supervision may be important in case continuous in-situ monitoring of scenes is demanded for instant human intervention. In such a case, the functional space shown in Figure 1 is to be supervised by human through monitor watching. Here the human perception plays an important role. The actual scene is surveyed by the cameras, and at this stage human perception is not in the play. However, the image of the functional space is propagated to a screen, and then the human perception via the screen becomes an issue of assessment. Such assessments should be quantified to understand the difference among the probable camera positions, or among cases where different number of cameras are used. It is emphasized that two, three, or more cameras may be used to cover the functional space entirely, as exemplified in Figure 1b and 1c, so that compliance with the consistency condition described above can be achieved in several ways that are not equivalent with respect to surveillance. As the human should realize the presence of objects and events in his mind, which is a complex brain process involving uncertainty, quantitative assessment of the human perception in the ambient environment surveillance case becomes desirable and is challenging to accomplish. Comparing the situations in Figure 1b and 1c, qualitatively three cameras in Figure 1c are favorable with respect to the human perception of the functional space, providing more visual information about the object to the human. Following the approach of existing works, such as Bhatt et al (2009), surveillance in Figure 1b and 1c is considered to be the same, as requirement consistency is treated as a binary statement. Binary verification of the requirement compliance is giving some indication about the effectiveness of the camera surveillance. However, this may be not enough for the case of human supervision, which is based on human perception. Based on this view, the present work intends to make some steps forward along this line, providing measured assessment about the quality of surveillance of an ambient environment based on perception modeling. Measured assessment is desirable in particular when optimal solutions are sought during design of an environment, for instance with respect to maximizing surveillance by optimal placement and orientation of sensors, or minimizing the number of cameras while sufficient surveillance is provided. We note that in this work we assume that there is no automated camera system for object recognition involved, although even in that case, differentiation among alternative camera utilizations, in order to determine the effectiveness of the machine recognition, still remains an issue.

The organization of the paper is as follows. The *methodology* section describes the treatment of the probabilistic and possibilistic aspects of the surveillance. The *computer experiment* section describes an example application of the method for an ambient environment, and the section is followed by *conclusions*.

METHODOLOGY

This research aims to make assessment about the quality of human surveillance of an object based on camera sensed information. When a human views a camera sensed scene on a screen, in order to give meaningful interpretation to the scene he infers the information about the camera position and orientation from the scene, without having been explicitly informed about these. This process of assuming of a camera position by human is called immersion. To model this early stage of the ambient environment analysis by human, probability theoretic computations are used to simulate perception of objects by a human, who is immersed in the scene at the camera viewpoints.

Probabilistic Perception Revisited

Due to the complexity of brain processes underlying perception, perception is to be modeled as a probabilistic event. That is, there is a chance to see an object, meaning the presence of the object is realized in mind, which implies a chance of overlooking the object, too. We can term this as the uncertainty of human vision (Rensink et al., 1997; Bittermann and Ciftcioglu, 2008). For a single unbiased observer this uncertainty is quantified as described in Ciftcioglu et al (2006b), Bittermann and Ciftcioglu (2008). Consider the basic geometry as shown in Figure 2a. *P* represents an observer's point, where he is viewing an object. We consider a *perception plane* located at distance l_o from the observer, and a *scope of vision plane* orthogonal to the perception plane, having the observer's point and the object in it. The intersection of the perception plane and the scope of vision plane is the *y*-axis. A line perpendicular to the perception plane, passing from the point *P*, is the *x*-axis. The observer has a visual scope in the scope of vision plane, defined by the angle $\theta_s=\pi/2$, which is termed as vision angle. He is viewing the object that subtends the angle θ_b-θ_a. An unbiased observer is modeled, i.e. he has no preference for any direction within the visual scope. This means the probability density function (pdf) with respect to θ is given by $f_\theta(\theta)=1/\theta_s$, as seen in Figure 2b upper. As the object subtends the perception angle θ_b-θ_a, it has an associated perception $P=\int_{\theta a}^{\theta b} f_\theta(\theta)\,d\theta=(\theta_b-\theta_a)/\theta_s$, shown by the gray shaded area in Figure 2b upper. *P* quantifies the probability the object is mentally realized by the observer. The perception can be computed along the *y*-axis in Figure 2a by radially projecting the object from *P* on the *y*-axis. It yields a line segment, spanning y_a and y_b, as seen in the figure. The uniform pdf with respect to the vision angle θ is given by $f_\theta(\theta)=1/(\pi/2)$ and corresponds to the follow-

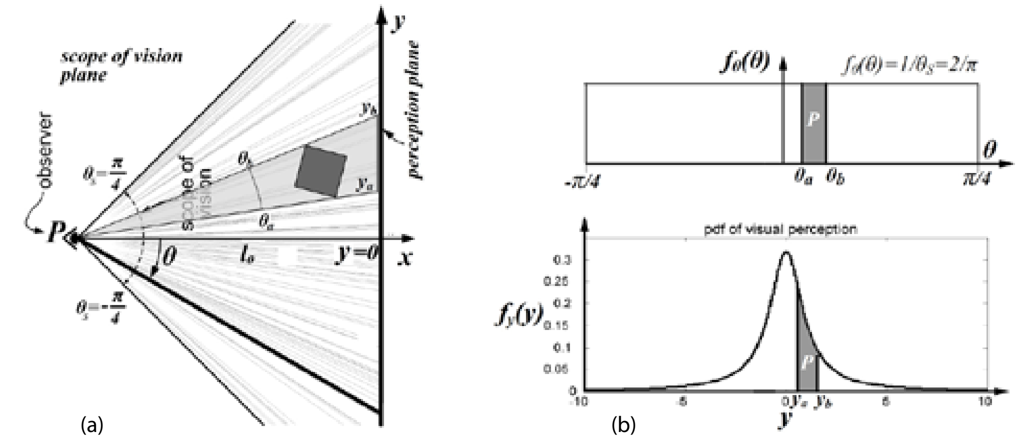

Figure 2
An object projected on the perception plane and perceived from P (a); sketch of the probability density function (pdf) characterizing perception with respect to θ (b upper); pdf characterizing perception with respect to the y direction for l_o=2 (b lower).

ing probability density with respect to *y* (Bittermann and Ciftcioglu, 2008)

$$f_y(y) = \frac{2}{\pi}\frac{l_o}{(l_o^2 + y^2)} \quad (-l_o \le y \le l_o) \tag{1}$$

The plot of (1) for $l_o=2$ is seen in Figure 2b lower. The perception is computed by

$$P = \int_{ya}^{yb} f_y(y)\,dy \tag{2}$$

and the result is shown by the gray shaded area in the figure. It is emphasized that the sizes of the gray shaded areas in Figure 2b upper and 2b lower are the same. We note that for the perception of a three dimensional object both vision angle and perception angle become respective solid angles.

Union of Perception Events

We emphasize that for the surveillance of the ambient environment being considered, the consistency requirement mentioned above stipulates that the functional space should be entirely encompassed by multiple cameras' fields of view. This means a human observing the scene will obtain the information from multiple cameras at the same time. In this respect we consider the case shown in Figure 1, where a single camera is not sufficient to comply with the consistency requirement, and in this study we consider the perceptions by means of three cameras, denoted *camera 1*, *camera 2* and *camera 3* in Figure 3. The scene subject to investigation is shown in Figure 3a, presenting a plan view of two rooms connected by a door and an associated functional space shown by a rectangular box around the door. The functional space is subject to surveillance via the three cameras, where the visible portions of this space respectively subtend the angles θ_1, θ_2, and θ_3 as indicated by the dark shaded areas in the figure. The dashed lines in the figure indicate the boundaries of the cameras' fields of view, where their associated angles θ_{S1}, θ_{S2}, θ_{S3} are taken to be the same in this example. The intersection among the three camera scopes form a universe of discourse for the surveillance events as shown in Figure 3b by means of bold dashed lines. We define the following three perception events within this universe as seen in Figure 3c. The event a human observer, who is immersed at *camera 1*, becomes aware of the functional space that is at the same time within the scopes of *camera 2* and *camera 3*, is denoted by event E_1. Conversely, the perception event from *camera 2* that is at the same time within the fields of view of *camera 1* and *camera 3* is denoted by E_2. In the same way, the perception event from *camera 3* that is at the same time within the fields of view of *camera 1* and *camera 2* is denoted by E_3. The regions in the scene corresponding to the events are shown in Figure 3c, where the space belonging to E_1 is delimited by

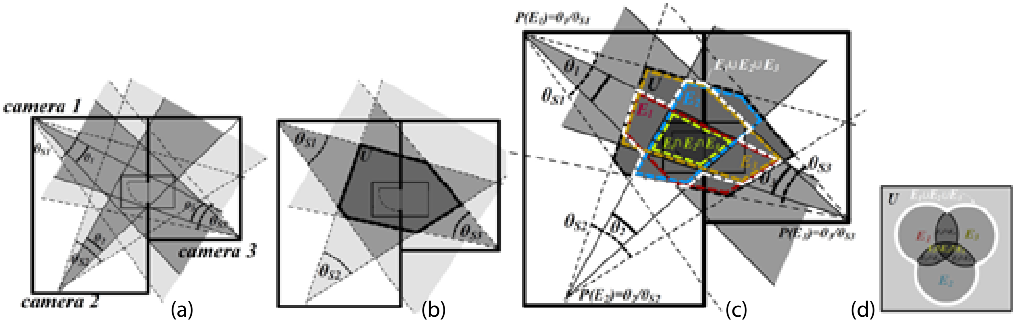

Figure 3
Functional space of a door subject to surveillance by means of three camera sensors (a); universe of discourse for the surveillance, where θ_{S1}, θ_{S2}, and θ_{S3} denote the respective fields of view of the cameras; perception events E_1, E_2, and E_3, their union, and intersection (c); Venn diagram corresponding to the events in figure 3c.

means of red dashed lines, for E_2 by means of blue dashed lines, and for E_3 by means of orange dashed lines. The probability of the perception events is obtained by $P(E_1)=\theta_1/\theta_{S1}$, $P(E_2)=\theta_2/\theta_{S2}$, and $P(E_3)=\theta_3/\theta_{S3}$. It is to note that E_1, E_2, and E_3 are independent events. With respect to ambient surveillance assessment being aimed for in this work, the event subject to computation is the union of the perception events $P_U=E_1 \cup E_2 \cup E_3$. The union refers the event that the observer becomes aware of the functional space either via immersion at *camera 1, camera 2, camera 3* or via combinations among them at the same time, while the consistency condition, namely that the event is to take place within all cameras' fields of view, is fulfilled at the same time as boundary condition. The region of space in the scene that corresponds to $E_1 \cup E_2 \cup E_3$ is delimited by the white dashed line in Figure 3c. The region of space in the scene that corresponds to $E_1 \cap E_2 \cap E_3$ is visualized in the same figure by means of a yellow dashed line. Figure 3d shows a Venn diagram corresponding to the perception events in Figure 3c.

The regions corresponding to the universe of discourse and encompassing the perception events are shown in 3D renderings in Figure 4. Figure 4a shows the fields of view of the cameras from top view in red color, as well as the cones encompassing the respective perception events E_1, E_2, and E_3 in yellow color. The same regions are shown in Figure 4b from a perspective view. Figure 4c shows the universe of discourse from top view and Figure 4d from a perspective view. Figure 4e shows the region corresponding to $E_1 \cap E_2 \cap E_3$ from plan view, and Figure 4f shows the same region from a perspective view. The probabilities $P(E_1)$, $P(E_2)$, and $P(E_3)$ are obtained by similar computations as given by (2) but for three dimensional space, where θ becomes solid angle Ω.

Converting the Probability into Possibility

It is emphasized that the computations above model the perception of observers, who are viewing the functional space being present at all three camera positions. However, the scene is actually viewed on a monitor screen and not directly from locations in the physical environment. That is, no actual object is being perceived in the ambient environment case, but a visual representation of the scene on a screen is being perceived. This yields the *immersion* phenomenon, which we can also term as virtual perception. In the ambient environment case, instead of perception alone an assessment of the perception is to be carried out, and this assessment should be expressed in possibilistic terms, namely as possibility of perception. This means the probability quantifying the perception of the object by the observer should be converted to a possibility of perception. This is shown in Figure 5. Figure 5a shows the perceptions of the functional space from the three cameras. The probability density functions $f_\theta(\theta)$ are integrated along angle dimension θ, yielding the perceptions $P(E_1)$, $P(E_2)$, and $P(E_3)$. It is to note that each of the three integrals have their center points at $\theta=0$ as seen in the figures. This is due to the surveillance purpose, where the cameras are oriented

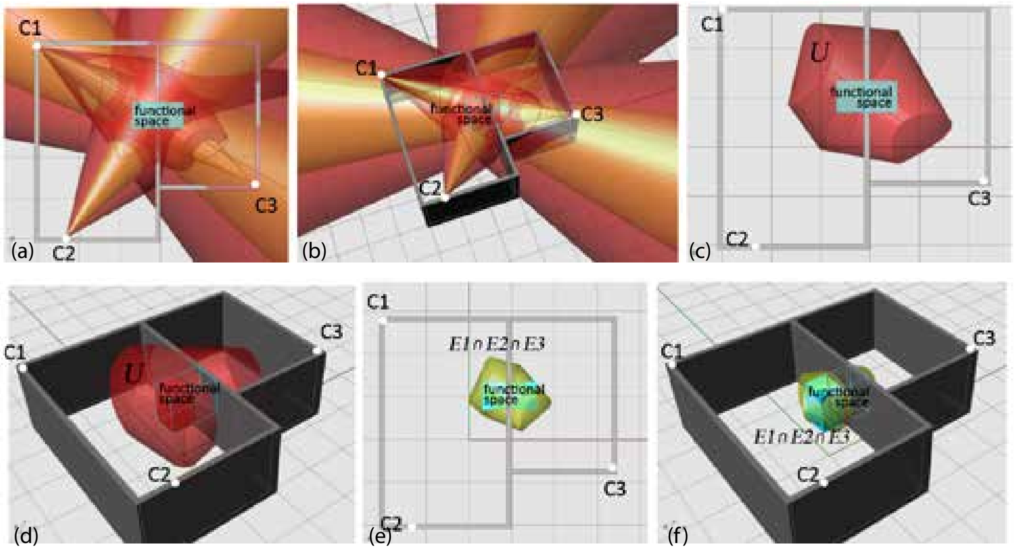

Figure 4
Fields of view of the cameras denoted by C1, C2, C3 and the cones in which perception events takes place from top view (a); from a perspective view (b); universe of discourse from a top view (c); from a perspective view (d); The region corresponding to $E_1 \cap E_2 \cap E_3$ from top view (e), from a perspective view.

in such a way that the object subject to perception is located at the center of the respective fields of view of the cameras. The probability of the union of the perception events $P(E_1 \cup E_2 \cup E_3)$ is shown by the hatched area in Figure 5b. Being an integral of the uniform pdf $f_\theta(\theta)=1/\theta_S$, $P(E_1 \cup E_2 \cup E_3)$ corresponds to an angle domain θ', as seen in the figure. It is noted that $P(E_1 \cup E_2 \cup E_3)$ is also centered at $\theta=0$ being the reference point of the perception computation in the scene as result of the immersion phenomenon. The pdf has a possibilistic density counterpart, namely a triangular possibility density function as seen in the figure. It is noted that the possibility density is maximum at the place that corresponds to the expected value of the uniform probabilistic density with respect to θ, namely $\theta=0$. Therefore, next to being the reference point for the perception computation simulating the immersion, the point $\theta=0$ also represents a reference point for perception possibility computation on the monitor, as zero refers to the center of the fields of views of the cameras, i.e. center of monitoring screen. For the possibility assessment, the possibility density is subject to integration over the angle domain θ', where the integration starts from $\theta=0$, yielding the dark gray shaded area in Figure 5b, the size of which quantifies the possibility of perception. It is emphasized that the integration starts from zero, i.e. in the middle of the screen, as to human perception, the possibility of perception is assessed starting from the middle of the screen. θ' starts from zero and maximally extends covering the interval $-\theta_S/2$ and $+\theta_S/2$, so that its maximum value becomes θ_S. Figure 5c shows a sketch of the relationship between possibility of perception versus the

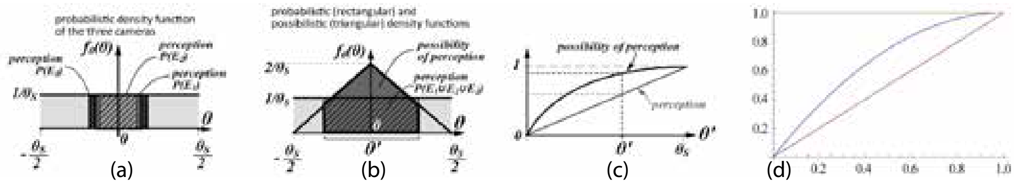

Figure 5
Perception of the functional space from one of the cameras (a); conversion of the union of the perceptions to possibility of perception (b); possibility of perception versus perception as sketch (c); as plot (d).

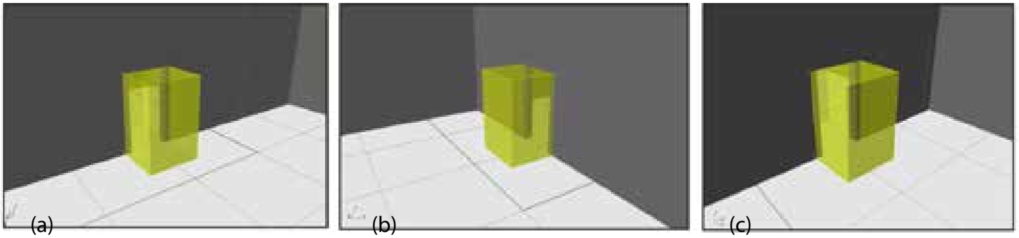

Figure 6
Camera picture taken from camera 1, where $P(E_1)$=.246 (a); from camera 2, where $P(E_2)$=.207 (b); from camera 3 where $P(E_3)$=.310 (c).

corresponding union of perceptions, and Figure 5d shows a plot of the same relationship. From Figures 5c and 5d it is seen that for a certain perception *P*, there is always a perception possibility having a greater value than *P*. As the perception is increasing, the associated possibility is also increasing in a non-linear way. In this treatment, obviously there is no possibility consideration if perception is not occurring. This means a triangular possibility density cannot be constructed without having referred to a probability density associated with perception. Such probability density is known to be attention (Ciftcioglu et al., 2006b). It is noted that shape of the function shown in Figure 5c is independent of the size of the scope $\theta_{S.}$

The possibility density function defined as a triangular fuzzy set shown in Figure 5b is the counterpart of the probability density function with respect to perception along the *y*-axis shown in Figure 2b lower. The form is precisely represented by the Cauchy function given by (1) that simulates the human perception in the scene as result of the immersion process. Both functions, namely triangular possibility density function and Cauchy probability density function, have a maximum at the respective reference starting points. This is confirmed by the common vision experience, that an observer is more aware of an object positioned in front of him, compared to a similar object that is located at some lateral distance from the former object. This is because the observer will remember more details of the former compared to the latter. It is noted that the shape of the monitor screen is not relevant to this computation.

COMPUTER EXPERIMENT

Based on the considerations above a computer experiment is carried out, where the possibility of perception is obtained for the scene shown in Figure 4 with the camera positions as indicated in the Figure. It is noted that the cameras are located at the ceilings of the rooms at the same height, and they are oriented in such a way that the central line of the cameras' fields of view are directed towards the center points of the respective visible portion of the functional space. The camera pictures of the scene taken from the three positions are shown respectively in Figures 6a, 6b, and 6c.

In the experiment, the unbiased visual attention given by the probability density per unit solid vision angle Ω given by $f_\Omega(\Omega)=1/\Omega_S$ and $\Omega_S=\pi\ sr$ is approximated by means of probabilistic ray tracing, in order to deal with geometric complexity of environment. In this treatment rays are sent in random directions from camera position, and the intersections with environmental objects are analyzed. The ray directions are generated in such a way that $f_\Omega(\Omega)=1/\Omega_S$ is approximately fulfilled, which is accomplished by using multiple Gaussian pdf as described in Ciftcioglu et al (2006a). Figure 7 shows the rays sent to simulate the perceptions via the three cameras. Figure 7a shows the rays that simulate the unbiased vision within the scope defined by the cameras' fields of view, from a plan view. These are termed as *vision rays*. The same rays are shown in Figure 7b from a perspective view. It is noted that in order to display individual rays, in the figure merely 200 rays per camera position are shown, although in the experiment 2000 rays are used for accuracy of the results. Figure 7c shows those rays among the vision rays that inter-

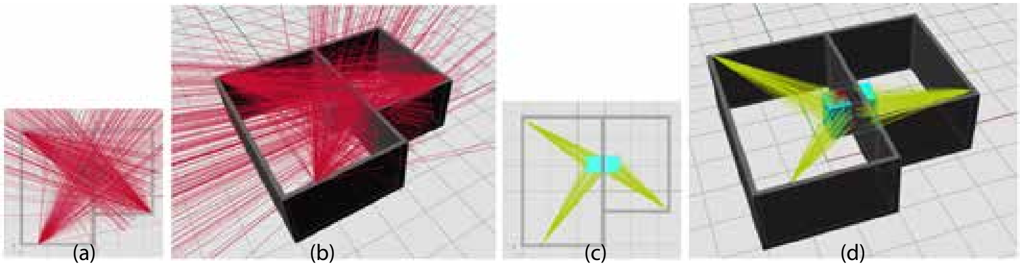

Figure 7
Vision rays from a plan view (a); from a perspective view (b); perception rays from a plan view (c); from a perspective view (d).

sect the functional space in a plan view, and these are termed as perception rays as they simulate the perception events E_1, E_2, and E_3. The same perception rays are shown in Figure 7d in a perspective view. The perception event *P(E)* is obtained by $P(E)=n_p/n_v$, where n_p denotes the number of perception rays, and n_v the number of vision rays.

The results from the experiment are $P(E_1)=.246$; $P(E_2)=.207$; $P(E_3)=.310$, so that $P(E_1 \cup E_2 \cup E_3)=.588$, yielding *possibility of perception* as $p_p=.830$. This quantifies the possibility of perceiving an event at the functional space of the door based on the camera positions considered. It is interesting to investigate what the difference in perception possibility is in case two cameras are used instead of three. Considering the case *camera 1* is not used, then $P(E_2 \cup E_3)=.453$, yielding the perception possibility as $p_p=.701$. In case *camera 2* is not used, then $P(E_1 \cup E_3)=.480$ yielding perception possibility as $p_p=.729$; and for *camera 3* being not used $P(E_1 \cup E_2)=.402$, so that the possibility becomes $p_p=.642$. Thus, compared to using two cameras, use of three cameras increases the possibility of perception by *18.4%, 13.9%,* and *29.3%* respectively for the three cases. It is also interesting to consider using only one camera compared to using three cameras. Using *camera 1* exclusively, the perception possibility is $p_p=.431$ so that the three cameras entail an increase of *93%;* using *camera 2* exclusively the possibility is $p_p=0.371$ implying an increase for the three cameras of *124%*; and in case exclusively camera 3 is used the perception possibility is $p_p=.524$ implying an increase of *58%* for the case of using the three cameras. This information is essential in determining the surveillance level of environments, and in particular provides information on the remaining surveillance in the case of a camera failure, which provides an indication of the robustness of a surveillance situation.

CONCLUSIONS

A probabilistic-possibilistic approach that models surveillance of a scene by human via three cameras is described. The first stage in camera based human surveillance is the immersion phenomenon, and this is modeled in the presented work by means of perception computations that are probabilistic in nature. These computations reflect the fact that remembrance of visual information processed by human vision system is not certain, i.e. it is subject to probabilistic considerations. The second stage of the surveillance is conversion of the perception into possibility. The possibilistic treatment accounts for the fact that the observation event does not concern perception of an object from an actual location in space, but perception of a camera sensed image of the object on a monitor. This way perception is assessed in the form of a fuzzy statement. In the same way as probability is due to integration of a probability density over some physical domain, so that it is associated to an event, possibility is computed by means of integration of an associated possibility density function belonging to the same domain. The domain in the present case is vision angle. The computer experiments presented in this paper confirm the qualitative statement, that the number of cameras influences the possibility of perception. The probabilistic-possibilistic treatment described in this paper uniquely quantifies this possibility, providing precision assessment of surveillance of ambient environments. This implies that through the novel approach, subtle differences among surveillance situations are distinguished, allowing for more conscious decision making. This may have important place in diverse applications, such as domestic healthcare, safety and security of buildings and cities, applying to both, existing situations, as well as during design of new environments. It is interesting to note that different stakeholders may use the method for different purposes, such as verifying if surveillance is sufficient, or verifying that it is not excessive, for instance for the sake of privacy of users.

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The Jacobs´ Urban Lineage Revisited

Analytical rudiments for the further development of the phenomenological approach to the study of the perception of people in urban space implicit in Jane Jacobs´ work

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Abstract. *Since the almost simultaneous publication of Kevin Lynch and Jane Jacobs´ seminal and pioneer urban manifestos, the discipline has been increasingly permeated by what could be rightly called the phenomenological impulse. While sharing methodological principles, however, they represent two very distinct approaches to the study of urban matters, a distinction rooted on their chosen object of study. The drawing of this distinction constitutes this research´s point of departure. Its fundamental aim is to help further the development of what we characterize as the Jacobs´s lineage of urban thought. To this end, the paper outlines methodological rudiments for the development of a methodological tool that would allow the beginning of a systematic study of the patterns of people´s presence and absence in urban space (streets). We call it Urban Polaroid. This work is part of a government funded (fondecyt 11110450) project.*
Keywords. *Urban phenomenon; phenomenology; Urban Polaroid; space syntax; Jane Jacobs.*

INTRODUCTION

Lewis Mumford famously branded Jane Jacobs` work as "home remedies for the urban cancer" (Miller, 1986). It was more than the derisive characterization of an opinionated and well-read urban scholar. It reflected the mood of a whole generation of urban planners that have systematically sought the source of urban knowledge in the study of the already built cities and how we perceive it. This archaeological kind of approach to urban studies has evolved, via Space Syntax, into a highly sophisticated and successful methodological corpus for the understanding of urban space. We call this the Lynch lineage of urban thought. This said, we argue that there is another equally distinct lineage. One that springing from Jacobs' seminal work- for reasons that will presently be discussed- has remained markedly underdeveloped. This lineage seeks urban knowledge not in the study of the perception of urban space (3D and 2D) but in the perception of that other highly differentiated spatial manifestation in the city: people. This paper offers methodological rudiments to further the development of this lineage. Its central argument connects with Hillier´s fundamental critique regarding urbanism´s historical and atavic tendency to dogmatically prescribe as well as to the sheer lack of analytical tools for urban analysis. It also connects with Ratti´s critique of Hillier´s work regarding the leap of faith implicit in Space Syntax predictions based on the axial map. It differs with both, however, in the object of study to which we apply ourselves.

DRAWING A DISTINCTION BETWEEN THE LYNCH AND THE JACOBS` LINEAGE.

Written from the point of view of a pedestrian sensible to the unique and ever understudied phenomenon of perceiving another human being, Jacobs manifesto Death and Life of Great American Cities (1961) was an open and frontal attack against the planning tradition advocated by leading figures such as Le Corbusier and Ebenezer Howard and their anti-autopoietic impulse towards the ruralization of the urban universe and the urbanization of the rural universe respectively. Both of them united by their reliability on the new means of transport as a solution to urban ailments, a stance widely trumpeted by Soria Matta and already implemented in two highly praised precedents: Barcelona´s *eixample* and the rebuilding of Paris. A school of urban thought that at least in the United States had by then become the school of choice of both, planners of academic pedigree and business speculators alike. It was the already proved pernicious consequences of this school of thought that Jacobs famously perceived in the economically informed interventions of Robert Moses in Manhattan.

Against this tradition, one of her prevailing concerns was, as she called it, "the social behavior of people in the cities", meaning by cities the streets we walk every day. Whereas it is a fact that her observations lacked rigorous analytical backup, her general methodological framework and object of study were unequivocal: the experience of walking through the city focusing on the patters of people presence. Not for nothing she is credited with having introduced the notion of "eyes on the street", by which she meant not "private eyes" but presence and co-presence in the Hillerian sense, particularly, that of residents.

Lynch´s urban approach (1960), on the other hand, was also rooted in the pedestrian´s perception, but this time, of urban space. That is to say, Lynch´s object of study was the perception of constant spatial patters through our daily navigation of the city streets, the current validity of his approach becoming manifest in freshly opened avenues of urban research (Morello and Ratti, 2008). Indeed, it has been this later lineage of urban studies the one that has seen the most dramatic developments in the last decades. This approach, characterized by its intrinsically archaeological nature, concerns itself with the perception of urban space- inhabited or in ruin like state- from a geometrical or topological point of view, depending on the placed emphasis.

A representative and consistent offspring of this lineage of urban studies is the ground breaking body of work developed by the Space Syntax Lab at the Barttlet School of Architecture, UCL in London and all that has sprouted from it. Hillier- its founder father- succeeded in developing a precise tool for the study of architectural and urban layouts, discovering in the process a close relationship between their topological configuration and the patterns of pedestrian flow they describe (Hillier, 1996). It has been its intrinsically non-discursive, phenomenological stance that has rendered most of its findings irrefutable, setting a new standard not only in urban analysis methodological consistency but also in urban data representation.

Another prolific offspring of this lineage has been the work developed at the Senseable Lab in MIT directed by Carlo Ratti. He and his team have mainly focused on the analysis of urban data in the form of electromagnetic pulses emitted by electronic devices (chiefly mobile telephones) carried by people every day during their daily urban navigations. Interestingly enough, it has been precisely Carlo Ratti, one of Space Syntax´s techniques most effective critics, who has brought Space Syntax principles to its last logical consequences by developing Digital Elevation Models (DEMs) with a view to complement Space Syntax reductive two-dimensional approach (Ratti, 2005). That is to say: a three dimensional version of Space Syntax that aims to incorporate sophisticated simulations of pedestrian movement and view sheds, among other factors.

This said, we argue that despite the great progress made by these representative techniques of urban analysis, they remain fundamentally speculative with regard to perception of people in space in the sense that none of them approaches it from an experiential point of view. That is, from the point of view of an embodied, walking subject. Indeed, whereas lines of research derived from Space Syntax´s developments have led to the development of agent-based models of pedestrian flow (Batty and Jiang, 1998), Ratti´s work has given rise to the "wiki city" notion, approach whose object of study is made up of electromagnetic signals emitted by electromagnetic devices (Calabrese et al., 2007a; 2007b; 2007c; 2007d; 2007e; Calabrese, 2008). In both cases, real people, understood as living human bodies, are nowhere to be seen. As a result of their eminently speculative nature, the predictions related to people´s presence on the street have remained potentially flawed in that they do not proceed from direct observation of people but from a priori speculations derived from computer models.

PEOPLE AS OBJECT OF STUDY

As it has already been amply discussed elsewhere, Jacobs and Lynch´s approaches were indeed tacitly grounded on a phenomenological standpoint (Seamon, 2012). This said there is a distinction that has not yet been clearly made. In phenomenology- at least in the case of the proto phenomenology of Goethean extraction- the fundamental law of knowledge generation is that this should be derived from a direct relationship with the chosen object of study. Thus the unequivocal Goethean admonition: "seek nothing beyond the object, they themselves, well contemplated, are the theory" (Seamon and Zajonc, 1998, p. 4)

Seen from this point of view, it becomes clear that the Jacobs and the Lynch´s lineages differ not in method but in their chosen object of study. Put differently, they differ on the source they turn to when in need of urban knowledge. Once this distinction is made, Space Syntax is revealed for what it is, namely, a very specific kind of urban phenomenology: a phenomenology of the city´s topology. One that gives us no direct knowledge about pedestrians patters of behaviour. Ratti has already pointed out that space syntax´s way of proving the connection between these two variables is by means of surveys. This is, by means of "a posteriori" correlations between the axial map results and observed movement data (Ratti, 2005). In the case of Ratti´s DEMs, we see a similar procedure applied this time to the study of view sheds. His strategy of electromagnetic signal tracking on the other hand brings us closer to the pedestrian who, nonetheless, remains an electromagnetic mobile signal. As for Batty´s agent based models, we already fall into a thoroughly speculative stance regarding the study of pedestrian behaviour. In sum, whereas space syntax´s approach to people study is post analysis (and at any rate not sophisticated as an analytical tool), Ratti´s and Batty´s are downright non-experiential.

Jacobs´s approach, although still in a rudimentary stage, was a phenomenology of embodied people perception, an object of study that from a methodological point of view proved to be very difficult to map due to it being a moving target, so to speak. Thus although the impulse latent in Jacob´s work can be traced back, through Hall´s proxemics (Hall, 1969; 1973; 1976), down to the rather unknown work of the German architect Herman Maertens (1884), it has ultimately remained analytically weak. The fundamental aim if this work is to help to further its development by means of introducing methodological rudiments that would allow a systematic mapping of the human universe, so to speak, thus complementing the successful efforts made by the phenomenologists of urban space.

URBAN POLAROID (A METHODOLOGICAL OUTLINE)

Acknowledging from the outset that all record of an experience is a reduction of it, the basic methodological principle is the following. If what we want is to know which are the patters of people presence in the streets of any given urban area at any given time, then what we need is a simultaneous photographic record of all the streets within the defined perimeter. In principle, this could be done in two ways. One of them is by means of satellite or drone´s aerial pictures. In this kind of record, people become dots on the street. Another way of achieving this without having to fly away from the streets is to resort to a photographic scanning of the streets at observer level. While we consider this later path to be a properly experiential one, its implementation presents considerable and at the same time, interesting practical problems.

Just like space syntax´s axial map calculus depends upon the distance from all to all lines or streets, in order to obtain an accurate estimate regarding actual presence of people in the street, we need to capture the state of all the streets within the chosen area of study at the same time. So for example, if the intensity needed to validate the reliability of the study is, say, 3 pictures by segment (or block) and the total numbers of segments (or blocks) that make up the street is, say 10, the total amount of pictures needed for this particular street would be of 30. Seen from an ideal point of view, this means that what we really need in order to obtain a true "instant" or "Polaroid" of this street are 30 different cameras (people) taking a snapshot (in the same format: height, level, lens aperture, etc.) at exactly the same time. This process in turn should then be repeated in all the streets contained within the chosen area. If the total number of streets within this chosen area is, say, 20, the amount of cameras (people) needed in order to get the Polaroid is 600. Since logistically this is extremely difficult and probably counterproductive- though not impossible-, we resorted to urban journeys or navigations. That is, video/photographic journeys along all the streets contained within the chosen area of study. The consistency and reliability of this approach will depend exclusively on the amount of journeys undertaken in a day, month and year per each street under observation.

CASE STUDY (CONCEPCIÓN, CHILE)

All the streets belonging to the historical layout of the city of Concepción are journeyed along (for a plan, see Figure 5). To this end, we created a patrol of photographic record composed of 26 students. The format established that every street should be walked in straight, from one end of the perimeter to the other, and that all journeys should start at the same time, in this case, midday. Unless impossible, the itinerary must be made through pedestrian areas only. While doing so, a video record from a constant observer level and with constant lens aperture is done. Depending on the amount of frames exported from the video record, we obtain a photographic record of variable intensity. That is, an "n" number of frames per street segment, understanding for segment, the length of the street defined between intersections with other streets or, if preferred, between corners. In this case, we used a low intensity: 2 pictures per segment. Arranged in filmstrip format, this raw, unedited record shows as a result a reduced general state of the behavior of our visual field during the journeys (Figure 1).

Applying simple raster graphics, we then proceed to transform, frame-by-frame, all visual information in the shape of human beings into colored surfaces, in this case, a red surface (Figures 2 and 3).

This first step has the peculiar characteristic of being quantitatively and qualitatively very eloquent in that it already reveals a great deal of information regarding the patterns of behavior of our visual field with regard to the presence of people in it. (We have defined three kinds of archetypal visual information to be found within the urban universe: information in the shape of people, information in the shape of urban space and information in the shape of nature. This paper only deals with the first kind.) That is, how much surface of our photographically reduced visual field is populated by information in the shape of people. Comparing the colored area to the total of the frame, we then obtain the percentage of visual information in the shape of people for that particular frame. Doing the same operation with every frame

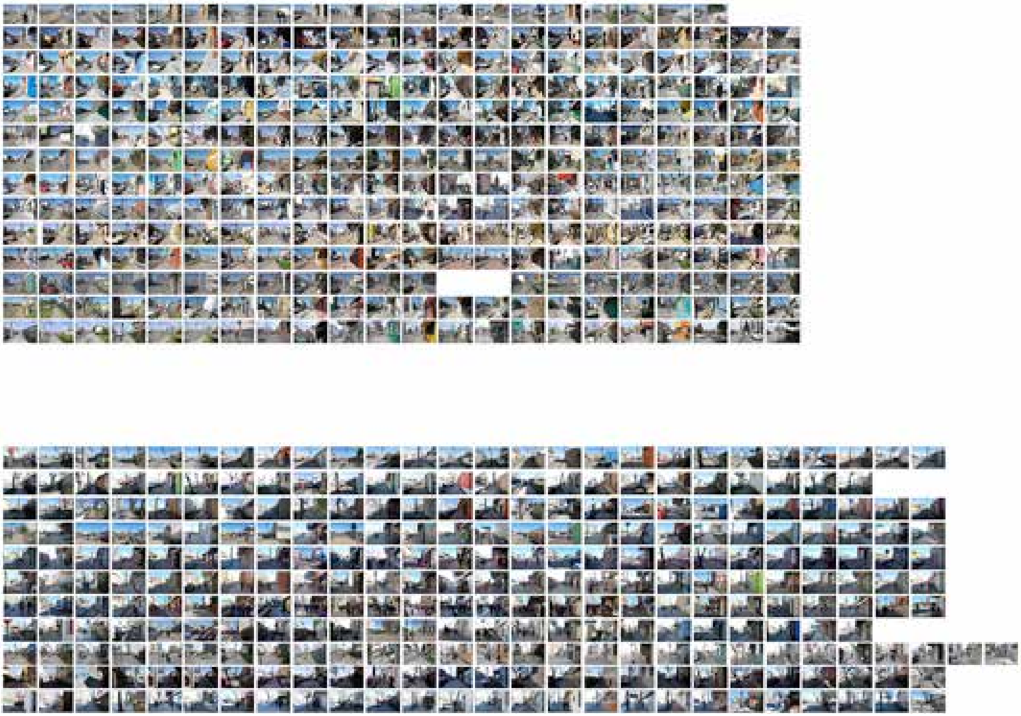


Figure 1
Photographic filmstrips of both, longitudinal (bottom) and transversal (top) journeys through the analyzed area.

of a particular street, we then obtain the average percentage of information in the shape of people for that particular street. Finally, repeating the same operation in all streets gives us as a result the average percentage of information in the shape of people for this particular city at the particular time in which the video/photographic journeys were done (Figure 4).

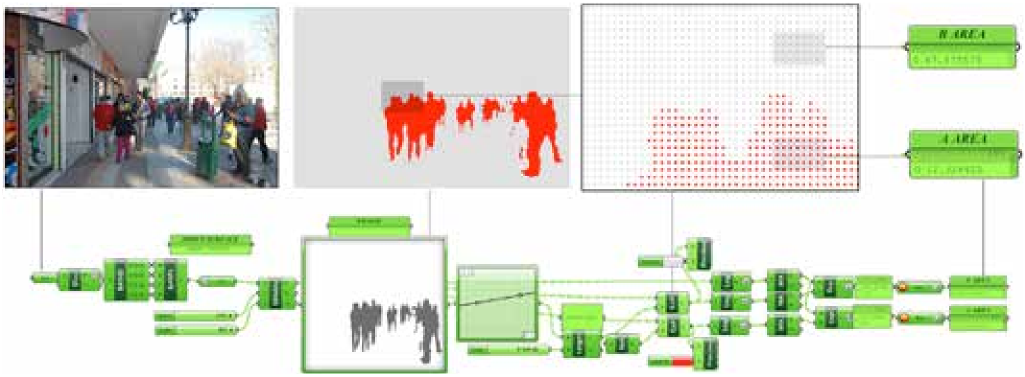


Figure 2
Rasterisation and calculus procedure for visual density of information in the shape of people of each frame.

Figure 3
Filmstrips of both, longitudinal (bottom) and transversal (top) journeys with information in the shape of people in raster form.

PRACTICAL CONTRIBUTIONS

We believe the most important contribution that the implementation of this tool brings about is that of effectively complementing the abstract archaeological approach developed so far by the Lynch lineage of urban thought. Indeed, whereas Hillier´s space syntax, Batty´s agent based computer models and Ratti´s DEM´s and signal tracking techniques (to name a few) tells us in which streets people are more likely to be found, the urban Polaroid reveals *ipso facto* where people effectively are. Put differently, by departing from actual experience, the urban

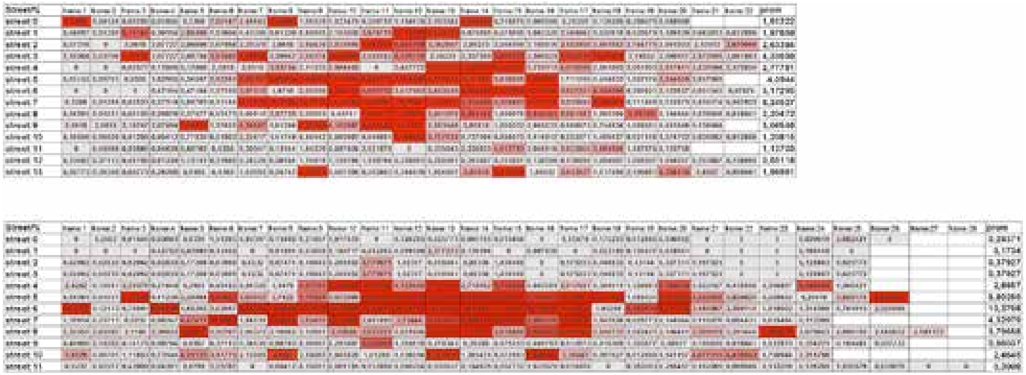
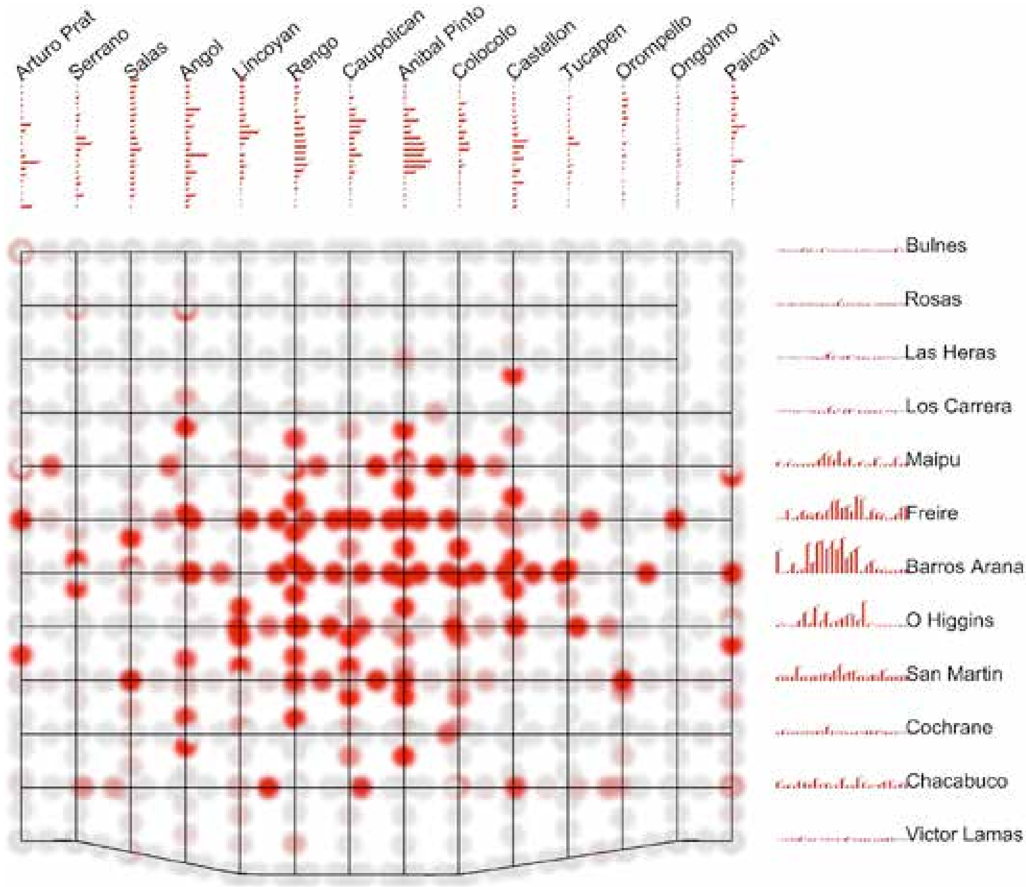


Figure 4
Table of quantitative levels of visual information in the shape of people per frame (columns) with averages per street (files) in the last column. Longitudinal journeys bottom, transversal journeys on top.

Figure 5
Two dimensional syntax of the levels of people presence per street.



Polaroid reduces to nil the speculation implicit in most of the urban tools of analysis developed by the Lynch lineage representatives. Indeed, transforming the table numbers into graphs, the result shows a remarkable similarity with space syntax findings (Figure 5).

Red, our chosen color for high visual people density, tends in this case to coincide with the axial map analysis result, which, if applied locally, would show the central streets of the chose area as the most integrated one. Hence, although the knowledge obtained via the two approaches is quantitatively akin- as it can be readily gathered from the diagrams they yield- they differ dramatically in quality. One showing potential, the other showing actuality; one being of interest only to specialists (particularly transport engineers and property developers), the other to urbanists and citizens in general; one revealing information about the already built city, the other about the city yet to be built.

THEORETICAL CONTRIBUTIONS

One of Jacob´s central declared concerns was to get to know "how a city works". What she called "the underlying order of cities" (Jacobs, 1961, p. 25). In line with Luhmann (1995), today we might say that Jacobs quest was for the discovery of the laws that secure the autopoiesis of the urban universe and, as a consequence of this, its perpetuation in time. If, as the Goethean maxim goes, theory building derives from direct object contemplation, then, in order to obtain urban knowledge, all we need to do is to find out which is the urbanist´s object of study. Jacobs was neither explicit nor sure about the answer to this question. Yet her main object of study always remained people on the streets.

Very few shared with her this interest. One of them was the urbanist Jaime Garretón, author of the first truly general urban theory, for whom "nothing is definite in a city, except its laws" (Garretón, 1975, p. 273), laws that, according to him, are essentially communicative laws. To be sure, the laws of communication between people. This said, neither Jacobs nor Garretón developed analytical tools for the study of their chosen object of study. To be more precise, neither of them built a systematic corpus of study cases and as a result of this, as Hillier would put it, they remained prescriptively strong but analytically weak.

By focusing on the study of people in space rather than on space itself, this paper represents a primeval impulse towards the development of general analytical rudiments for the further development of the Jacobs´ lineage. Whether the urbanist´s own object of study is urban space or people remains too big a question to be answered in these pages.

CONCLUSIONS

Even at these early rudimentary stages, the Urban Polaroid technique of urban analysis has demonstrated to be a most useful as well as didactical complement to the abstract techniques championed by the Lynch lineage advocates. It does not only allow the systematic exploration of a thoroughly understudied, parallel universe, to the one by them explored. More important still, by being grounded in experience, it renders unnecessary all speculation regarding patters of people presence inherent in abstract computer aided analysis. This might prove crucial in the cases where the axial map analysis does not conform to actual reality of a determined street or area of the city. Moreover, it achieves this without the need of people carrying mobile phones or any kind of microchips. This makes it less invasive and more citizen friendly.

Future complementary applications include a Polaroid of the visually perceived built universe and another of the natural universe, aspects that might throw light upon the other two archetypal kinds of visual information in the city and the relationship between them. In sum, the Urban Polaroid approach offers a portrait, and as such, a reduced view of a complex that we have called the "archetypal citizen", according to previous research, the urbanist true object of study (Araneda, 2008; 2010; 2011).

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Collaborative and Human Based Performance Analysis

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Abstract. *This research presents methods for simulation and visualization of human factors. This allows for a performance based analysis of buildings from the local human scale to the larger building scale. Technical issues such as computational time and mathematically describing a buildings geometry are discussed. The algorithms presented are integrated in a 3D modeling software commonly used in design and architecture through a plugin.*
Keywords. *Universal design; human analysis; collaboration; education; disability.*

INTRODUCTION

In general, the field of Building Information Modeling (BIM) is related to structural or environmental analysis. This is likely due to the main users of BIM: Architecture, Engineering, and Construction (AEC). By utilizing BIM approaches these fields are able to reduce human error and cost from design to construction (Azhar et al., 2008). While BIM can include many forms of analysis, human factors have not traditionally been included. Additionally, the definition of BIM is still being debated and developed (Eastman, 2008). For this reason, this paper concentrates on the term *building performance* to discuss the relationship of human factors to overall building analysis. However, this term is only for clarity, and the work presented is wells suited to be integrated as a feature of BIM software.

As with BIM, building performance is largely focused on structural and environmental factors that can be quantified. When the human is included in an analysis of building performance it is usually related to the environmental effects of a human, or multiple humans, such as heat transfer or acoustical properties (Mahdavi, 2011). There are a few reasons the ergonomic and physiological aspect of humans are not usually considered necessary to include. For one, many important aspects of a building in regards to humans are regulated in laws, for example, the American Disabilities Act (ADA) (Dept. of Justice, 2010). Similarly, many of the components related to humans are standardized, which has been needed as the AEC community is not focused on researching ergonomics or biomechanics, large research fields in themselves. Additionally, excluding emergency situations, the cost of an error in construction is much greater than a door knob being difficult to use. While these reasons are valid, they only represent the minimum of what design can be.

The philosophy of Universal Design brings to question the lack of human factor analysis for building performance. Exclusion of human factors from the design and analysis stage while relying on standards and prescribed law can be stigmatizing and may need to be fixed later, demonstrating the failure of design (Story, 1998). While the ADA is specific to disabilities, Universal Design is meant to benefit all people. Universal Design has become part of many curriculums in architecture schools (Vance, 2012), however, understanding the problems with designs related to human factors can require costly physical experiments or communication with experts in other fields. Schubert et al. (2011) present a method for integrating physical tools with the design workflow, and Maver et al. (2001) demonstrate the ways in which universal design concepts can be explored through virtual reality. Although both of these present alternative methods to real world experimentation, they still require physical space and money.

This paper is meant to function as a reference on the types of quantifiable human factors, an approach to education, and a method for collaboration between the complicated fields of ergonomics and biomechanics with architecture and design. A 3D Manikin plugin is presented with a graphical user interface allowing access to the underlying algorithms that simulate and visualize human factors of the manikin with the space at different scales. Algorithms written in python are presented for five main areas: Reach, Vision, Zone, Search, and Movement. Aspects of biomechanics software are integrated with the plugin to create a platform for collaboration. To cohesively demonstrate the application of each component a manikin in a wheelchair is used.

METHODOLOGY OF COMPONENTS

There are many components to building design that effect human performance. The methods described in this section describe both human factors that should be addressed as well as methods in which to perform the simulation, however, this list is not exhaustive. The methods describe the algorithms used in the plugin written for MAYA, but can be applied in almost any 3D modeling tool.

Reach

While every person is slightly different in their ability to reach, the effects of a disease or spinal cord injury on reach ability (Jacquier-Bret et al., 2008) is important to know. A large problem with the ADA standards is the assumption that a person in a wheelchair is only limited in leg functionality. As this is not true, the ability to simulate reach ability for different users allows for a performance based analysis of the environment by comparing the reach ability to desired reach locations. The inverse kinematic (IK) system used to control the manikin arm was developed in MAYA, however, additional research into disability reach would greatly improve the simulations. Currently one of the most used and advanced simulation tools for ergonomics uses a reach envelope, visualizing the extent of a persons reach (Blanchonette, 2010). This is generally okay when a user is able to rotate to one side or another, however, if the user has a specific type of reach ability a more complete map needs to be simulated.

A voxel volume was used to create a complete 3D map of the reach ability. Each voxel is given a value based on the ability for the IK solver to find a solution for the voxels around the initial voxel as seen in equation (1).

$$\vec{r} = n_x\hat{x} + n_y\hat{y} + n_z\hat{z}, \text{ where } \vec{r} \in V$$

V is the set of all points in the volume.

$$\vec{r}_i = l\hat{x} + m\hat{y} + n\hat{z}, \text{ where } l, m, n \in \{-1, 0, 1\}$$

$$f(\vec{r}) = \sum_{\{\vec{r}+\vec{r}_i \mid \vec{r}_i \in N(\vec{r})\}} 1$$

$$\text{Where } N(\vec{r}) = \{\text{reachable neighbors}\} \quad (1)$$

Physically, this means if a persons hand is in an initial position, that position is ranked based on how many ways the hand can leave that position. The summation over 1 can be modified for a more elaborate or specific analysis of the reach ability volume. For instance, by changing 1 to the distance from the shoulder multiplied by gravity, areas further away from the body will be given lower scores than those closer. In the case of spinal cord injuries, this value can reflect the joint angles required to reach a position. The visualization corresponds to the simulation results such that opaque green voxels are the highest ranking and transparent red voxels are the lowest ranking. The method for coloring voxels, without transparency, is similar to robotics work in which the workspace must be defined and visualized (Zacharias et al., 2007). The visualization can be seen in the results section.

Vision

Designing with a persons vision in mind requires two aspects, items that should be seen, and items that should not. The former case includes items such as signs and navigational cues, while the latter includes direct lighting. An important aspect of vision is neck mobility. If for instance a person is in a wheelchair, the range of movement in the neck may be limited. In this case, as well as in many elderly people, it cannot be assumed that a building occupant will turn their head to view an item. In the case of direct lighting, many times a person will be uncomfortable, or worse, unable to see in the distance resulting in a dangerous situation.

The importance of vision is well known in architecture and design. In Tilley et al. (2001), a diagram showing many aspects of the human vision is used as a reference for designers. The problem with the diagram is the difficulty in understanding and translating the content to ones own design within both practice and education. The diagram can be represented in 3D space by referencing both top and side maximum angles. For displaying the vision regions each one of the four points, referred to as *Limit*, that describe the region are input at both an initial distance and the distance to where the visualization should end. Equation (2) shows the formula to calculate where each point should be placed.

$$\sqrt{\left(\frac{\text{distance}}{\sin(90-\text{Limit})}\right)^2-\text{distance}^2} \quad (2)$$

In order to analyze the building for direct lighting at a specific point the location of the manikin head as well as direction is calculated in regards to each light. According to the diagram in Tilley, the disability glare zone is 45 degrees above the persons eye level and the extent a person can see to the side is 94 degrees. The domain is found with two calculations. First, the angle above the eye level is found creating a right triangle between the head position and light position with the hypotenuse being the distance between the two points. The adjacent side is the horizontal distance and the opposite side is the vertical distance. The algorithm for determining if the light is within the vertical 45 degree angle is seen in (3).

$$\tan^{-1}\left(\frac{\text{Horizontal Distance}}{\text{Vertical Distance}}\right)<45 \quad (3)$$

Second, the location of the light relative to the head must be found. For this, a reference point is placed at any distance in front of the head in the direction it is facing. A triangle is constructed from the head position, reference position, and light position with the light projected onto the head up axis, assuming *y* is the up axis (4).

$$\begin{aligned} a &= \sqrt{(\mathrm{H}_X-\mathrm{R}_X)^2+(\mathrm{H}_Y-\mathrm{R}_Y)^2+(\mathrm{H}_Z-\mathrm{R}_Z)^2} \\ b &= \sqrt{(\mathrm{R}_X-\mathrm{L}_X)^2+(\mathrm{R}_Y-\mathrm{H}_Y)^2+(\mathrm{R}_Z-\mathrm{L}_Z)^2} \\ c &= \sqrt{(\mathrm{L}_X-\mathrm{H}_X)^2+(\mathrm{L}_Z-\mathrm{H}_Z)^2} \end{aligned} \quad (4)$$

where *H* is the Head position, *R* is the reference position, and *L* is the light position. Using the law of cosines, the side angle is calculated and checked against the 94 degree limit (5).

$$\cos^{-1}\left(\frac{c^2+a^2-b^2}{2ca}\right)<94 \quad (5)$$

The lights found to be in the disabling glare zone can be marked in the model and the total number can be displayed for the designer.

Zone

The space around a person can be classified in multiple ways. There is the space someone needs to be physically present, space that makes someone comfortable, and space in order to complete a task. The latter two are most often related to psychology as well as physiology. The importance of the space around a person can be seen in design reference books (Zelnik and Panero, 1979) as well as in research papers (Lantrip, 1993). When designing the spatial needs of a wheelchair the designer must understand the many situations that exist. For example, if a hallway is designed to be wide enough for a wheelchair to pass through, it may not be wide enough for the wheelchair to turn around, or more commonly, for a person in the opposite direction to pass by.

The implementation of a spatial zone is relatively easy in a CAD program. The spatial zone needed can be visualized by a transparent cylinder around the manikin as seen in the results section. In the case of multiple people more than one cylinder can be displayed. The coordinates in the mesh are generated the same as in (2) where *Limit* is defined as the distances from the center of the manikin. As the generated mesh contains a Cartesian domain, it is possible to analyze environmental interference in regards to the generated geometry.

Search

Out of many human factors that can be included in building analysis, the distance and way in which someone moves throughout is one of the most difficult to integrate, yet is extremely important. While laws exist for wheelchair ramps and elevators, knowing how a building layout or size affects the occupants is required to design above the minimum. There are many forms of analysis of human factors that are useful at the human scale, including egress and accessibility. Two components needed to analyze movement throughout a building are: mathematically describing the building and creating the path of movement. From this it is possible to run numerous simulations of human factors to analyze the path created. The current implementation refers to the path as the energy required.

The easiest way to describe a building using a node graph is to make landmark areas nodes and create connections, known as edges, between them. When the fastest way between two nodes is desired, a search algorithm calculates the edge values from one point to the other (Dijkstra, 1976). In general, the distance between each landmark is the value given to the connection. However, the distance between each landmark must be the length of the route from start to end, not the Cartesian distance. This creates a problem when attempting to translate a 3D model of a building into a searchable graph without individually measuring each path (Figure 1).

Using the internal raytracing function of MAYA, a technique was developed for mathematically describing a 3D model of a building. The first assumption is that any geometry that should be considered as ground should begin with the naming convention

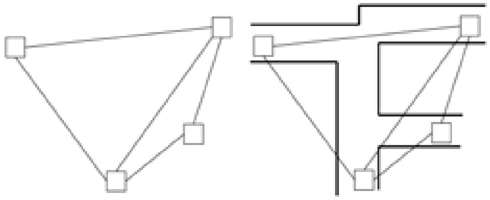

Figure1
Left: Key locations exist in Cartesian space. Edge values are the distance between them. Right: If the building walls are included it is easy to see the problem with calculating distance directly.

"floor". Anything following that name is irrelevant and can be used for the designers own organization. The second assumption is that the manikin is placed over any valid ground. If these conditions are satisfied, the algorithm will send a ray from the top of the manikin head to the floor and return the Cartesian position. Each valid ray is checked against the minimum required space, in this case, a wheelchair turning radius. The algorithm then expands outward and continues to store valid node locations as seen in (6).

Let $C_i = \{\vec{r}_k \mid |\vec{r}_k - \vec{r}_i| = R\}$

Where R is the wheelchair turning radius.

$$N = \{\vec{r}_i \mid \forall \vec{r}_k \in C_i, \vec{r}_k \text{ is on the floor}\}$$

N is the set of valid nodes. Let $\vec{r}_{ij} = \vec{r}_j - \vec{r}_i$ and a be the spacing between nodes in the x, y plane. (6)

The edge values are the key to analyzing the building. As each node is created, so are the edge costs to each of the available nodes surrounding it (7).

$$E = \{(\vec{r}_i, \vec{r}_j) \in N \times N \mid (\vec{r}_{ij} \cdot \hat{x})^2 + (\vec{r}_{ij} \cdot \hat{y})^2 = a^2\}$$

E is the set of edges.

$$f(\vec{r}_i, \vec{r}_j) = g(\theta_{ij}) \text{ where}$$

$$\tan\theta_{ij} = \frac{\vec{r}_{ij} \cdot \hat{z}}{\sqrt{(\vec{r}_{ij} \cdot \hat{x})^2 + (\vec{r}_{ij} \cdot \hat{y})^2}}$$

$g(\theta_{ij})$ is a value function that assigns energy cost to each edge based on the angle of inclination. (7)

Figure 2
The GUI inside of PYQT. The tabs can be seen on the top.

Altering the edge cost can be useful to analyze different situations such as the path of a wheelchair or a person with crutches. For example, implementing this algorithm for a wheelchair would be done by making any edge that is at a slope, larger than the maximum required by law, an infinite value. By returning a path through the nodes, the physical distance can also be calculated. As each node has a total value assigned to it by the connecting neighbors a visual representation can also be created.

Movement

As previously mentioned, one problem with fully in-

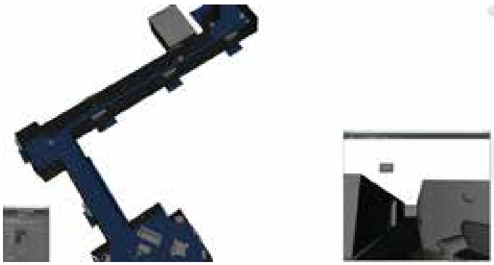

Figure 3
The MAYA window with a new camera perspective of the manikin in the lower right.

tegrating human factors in design workflows is the extra knowledge of human biomechanics required of designers. As both a teaching and collaboration tool, this research demonstrates a method for integrating the two fields.

Many types of analysis in biomechanics use joint angles. To integrate this workflow a python library for creating matlab style graphs (Hunter, 2007) was implemented within the plugin. As some design modeling tools do not have animation features, all time related elements are stored in comma separated value (CSV) files. The file structure implemented is the same as those from the exported joint angles of biomechanics software.

Graphical User Interface

Combining the algorithms together and linking them to the 3D modeling software is done through callbacks and signals within a graphical user interface (GUI) (Summerfield, 2007). The GUI is designed to give the designer access to all of the variables within the algorithms. Each component is given a separate tab in the GUI with a full range of settings and variables (Figure 2).

RESULT

The implementation of the algorithms resulted in a cohesive tool that integrates with a 3D model of a building. A variety of visualizations, simulations, and analysis are available for the designer to use. As the building is being designed the only requirement of the designer is to place the manikin in a desired location. Once the manikin is placed, the designer can use any of the default settings to run the simulations. As shown by Eriksson et al. (2000), there is great value in participatory planning. This plugin allows for participatory planning by creating a second window in which the view of the manikin is displayed (Figure 3).

As it is not realistic to expect all architecture schools to have time for real world experiments, or access to wheelchairs, it is important to have a virtual method of exploring the same topics. During the early stages of this research a Universal Design

Figure 4
Left: Student points out objects in the way of navigation. Top-right: the path from manikin to a location is drawn. Bottom-right: objects placed over the ground are accounted for, creating a path that avoids the object.

class led by Sean Vance at the University of Michigan was documented (Vance, 2012). The students were not aware or directly influenced by this research. Multiple physical experiments were conducted by the students to simulate the relationship of disabilities to the built environment around them. While it is very useful for students to have a hands-on knowledge it may not always be possible. The tool presented here is capable of simulating and visualizing the same ways in which students felt the problems needed to be addressed. Some of these issues include obstacles in the way of a wheelchair (Figures 4 and 5), the line of sight from a person in a wheelchair (Figure 6), and items out of reach (Figures 7 and 8).

While it is possible to quantify all of the presented human factors relative to a building model, the largest scale quantifiable factor is in navigation. The graph search algorithm is very flexible and can be used for a variety of situations, one of which is seen

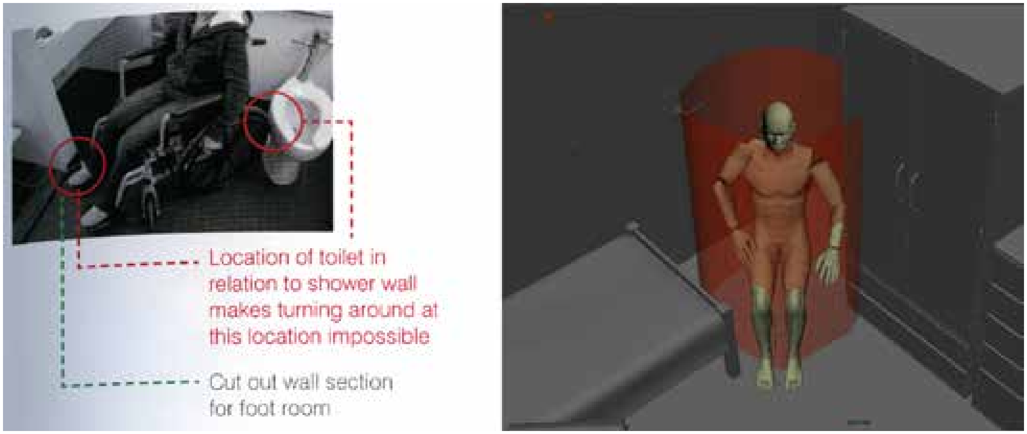

Figure 5
Left: Student points out problems with the distance between toilet and wall for turning radius. Right: Wheelchair dimensions are visualized in a 3D model of a room.

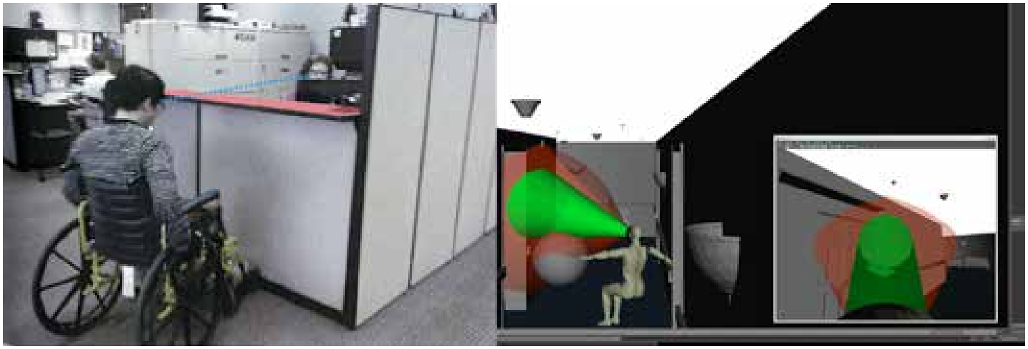

Figure 6
Left: Student draws line of sight to point out the difficulty in communication due to the high partition. Right: Two different vision cones are visualized. Two perspectives are shown, one from the building participant and a normal 3D model view.

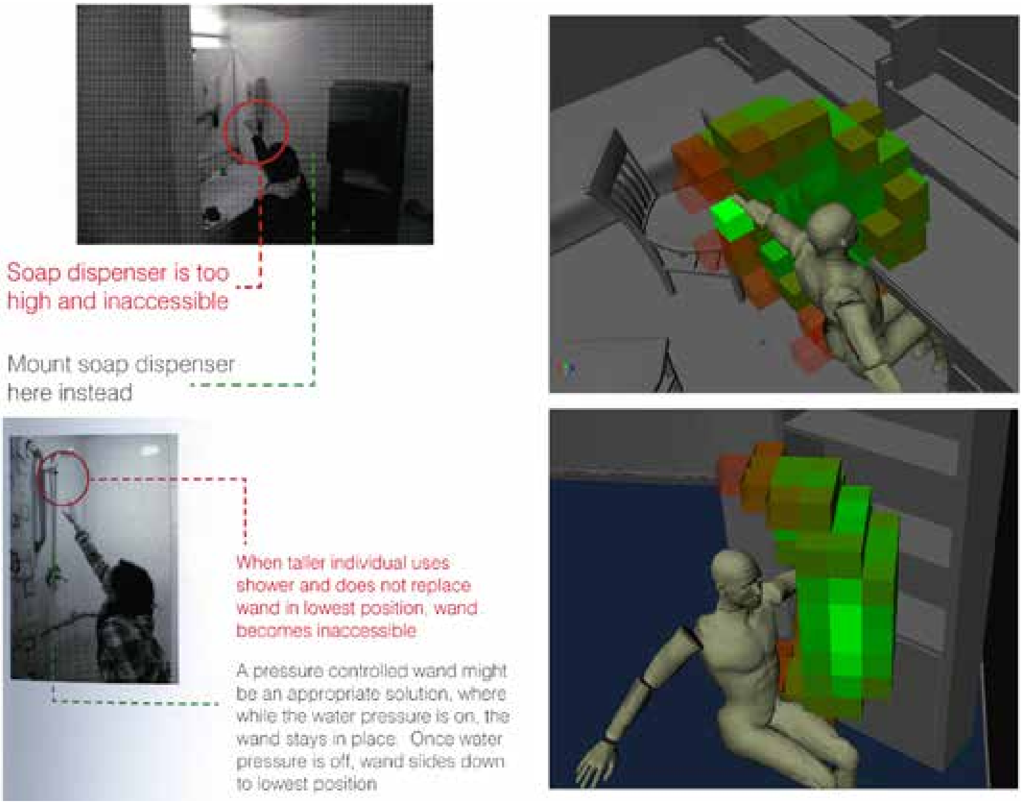

Figure 7
Left: Student shows problems with the placement of different items in a room. Right: The reach ability map is simulated and visualized with transparency and color.

in Figure 4. Another aspect of the graph search is the ability to analyze the amount of time it takes for someone to move from one point to another. In the case of a wheelchair, depending on the type of dis-

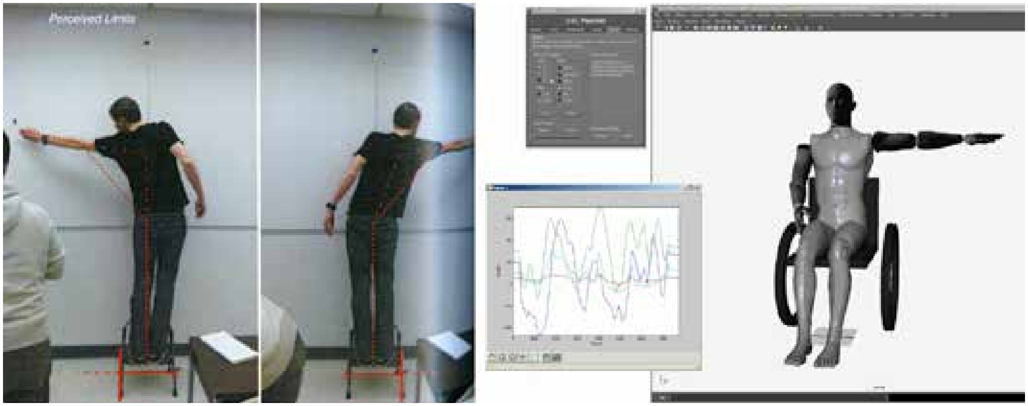

Figure 8
Left: Student drawing angles of human body to analyze limits. Right: Motion capture data of reach is displayed through a graph.

ability and wheelchair, a person will move between ~50 and ~80 meters per minute (Beekman et al., 1999). Taking data from a subject with paraplegia in a standard wheelchair a rate of 75 meters per minute can be used for analysis. When a designer runs the search algorithm the GUI will display the amount of time it takes to move along that path (Figure 9).

In addition to the speed of movement it is possible to calculate the energy expenditure of a movement. While there is a lack of human subject testing that can give an accurate simulation for all terrain, some basic estimations can be made. This approach can be used when designing a ramp and the designer is deciding if the ramp should be short, with the maximum allowed slope, or longer with a lower slope. As the search algorithm will find the lowest cost method to get to the end point, if the algorithm creates a higher cost of movement for a steeper incline, the path generated will reflect the best method. This situation is ideal for bringing in a biomechanics expert, or in the case of education, biomechanics students. As the biomechanics side is able to analyze the movement of a person during wheelchair propulsion and quantify the results, the design of the ground floor can be changed. Using this alongside the colored visualization shown in Figure 8 creates an opportunity for informed iterative design.

CONCLUSION

This paper presents a variety of functions, algorithms, and systems that can better integrate human factors with the design workflow. Each algorithm has potential to be both improved with speed and expanded on for functionality. The significance of the work is not limited to BIM and Building Analy-

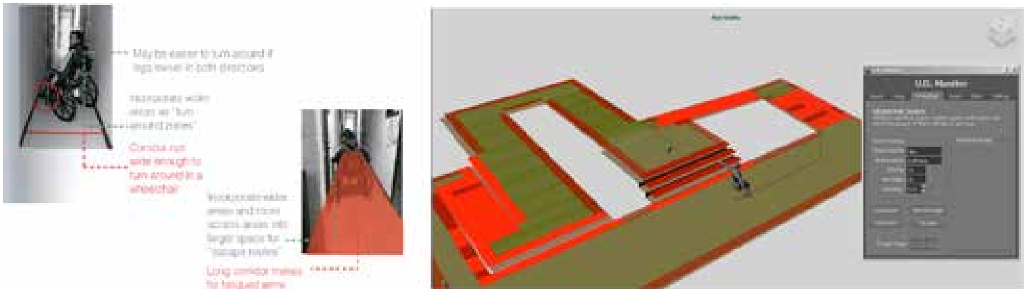

Figure 9
Left: Student demonstrates the narrow hallway does not allow for a wheelchair to turn around. Student notes the length of the hallway with no outlets can cause arm fatigue. Right: GUI Displays estimated time to travel using a wheelchair. Color coded ground shows results of simulated values. Red areas show either narrow hallways or a steep slope.

sis, but can bring human factors to the forethought of designers and architects, greatly influencing the style in which designs are created and simultaneously benefiting the building occupant. Recognizing the impossibility of designers to be a master of every field related to human ability, and the advantages of expert collaboration, a system has been presented in which biomechanics, architecture, and design can collaborate. Although some schools have been able to implement physical experiments to teach students Universal Design, many schools do not have the resources for these lengthy and costly experiments. Integrating human factor simulations in design programs would allow for students to learn the same basic principles.

ACKNOWLEDGEMENTS

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Visibility Analysis for 3D Urban Environments

Research development and practical application

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Abstract. *This paper presents a visibility analysis tool for 3D urban environments and its possible applications for urban design practice. Literature exists for performing visibility analysis using various methods and techniques, however, tools that result from such research are generally not suitable for use by designers in practice. Our visibility analysis tool resides in Grasshopper, Rhino. It uses a ray casting method to analyze the visibility of façade surfaces from a given vantage point, and of a given urban setting, in particular, buildings and roads. The latter analysis provides information on the best visible buildings/ building facades from segments of roads. We established a collaboration with a practicing architect to work on a design competition together, using this tool. The paper elaborates on the visibility analysis methods, presents the tool in detail, discusses the results of our joint work on the competition, and briefly reflects on the evaluation of the use of the tool by design practitioners.*
Keywords. *Visibility analysis; pedestrian design; urban space quality; design practice.*

INTRODUCTION

This paper presents a visibility analysis tool for 3D urban environments and its possible application for design practice. Visual perception of space is one of the factors that defines spatial experience and cognition of architectural/urban space. Analyzing the impact of design decisions on perception of space may help to significantly improve the quality of urban developments (Bittermann et al., 2008).

Many design and architectural researchers investigated the relation between urban space morphology and its experiential qualities as perceived by users. Among them are Appleyard et al. (1964), Lynch (1960), Benedikt (1979), and Thiel (1961). Kevin Lynch stipulated on the importance of view analysis and methods of analysis using terms such as “visual absorption”, “visual corridor” or “visual intrusion” (Lynch, 1976). A view analysis example is an ‘isovist’ analysis which measures a volume of space that is visible from a single point in space. The term was introduced by Tandy in 1967 (Tandy, 1967). This research gave raise to the development of a multitude of methods for quantitative analysis of space perception. Benedikt was the first who introduced a set of analytic measurements of isovist properties (Benedikt, 1979). In the field of landscape architecture and planning there is a similar concept called “viewshed” (Turner et al., 2001), which analyzes the visibility of an environmental element from a fixed vantage point.

Quantitative methods for visibility analysis can be roughly divided into the following categories: a) scientific landscape evaluation (LE) provides methods for 'quantitative description of natural landscape visual quality or impact prediction' (these approaches do not consider human perception); b) methods such as 'isovist' concentrate on the visibility of an environmental element from a fixed vantage point and neglect the landscape resources (He et al., 2005).

The most common examples of utilizing visibility analysis methods and tools in the field of urban design are analysis of visibility from important (strategic) points (e.g., large transportation hubs, major public spaces, etc.) to dominants (e.g. tall buildings, monuments, etc.), which can help to improve navigation of pedestrians in the city. Another case is the preservation and/or strategic use of views to natural landscape elements such as a river or park. This is especially relevant to high-density urban areas that are still undergoing an extensive development process, such as Moscow, Hong Kong or Singapore. Uncontrolled development in such big cities leads to fragmentation or complete blockage of views to valuable landscape resources, which are more desirable for people than man-made structures (He et al. 2005). This results in a drop of real estate values and deterioration of city fabric. In this context, He et al. (2005) presents an approach to visual analysis of high density urban environments, which quantitatively integrates human visual perception (analysis from a fixed vantage point) with the visible landscape resources (LE), using GIS as database and technical platform. This approach can help architects to take more informed decisions at an early design stage regarding the preservation of valuable landscape resources and view corridors. Another example is the work described in Fisher-Gewirtzman et al. (2005), which compares various coastal urban morphologies with the variation of density levels and their influence on the visibility of the water front. The assumption is that the morphological results can be used as criteria for future urban planning.

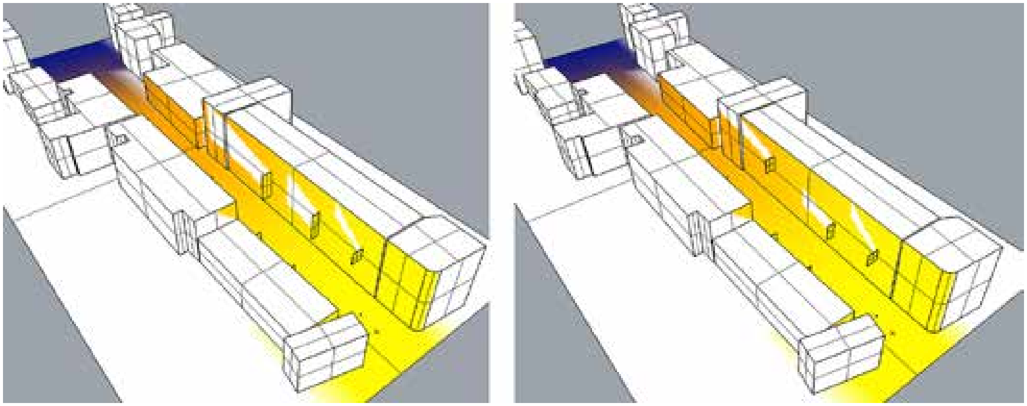
Do and Gross (1997) present a set of tools for spatial analysis among which are tools for visibility analysis performed using different computational implementations. The research underlines that different computational methods tackle different aspects of spatial analysis and provoke different ways of thinking about a problem. Therefore, a computational tool can become a flexible element that supports creative thinking during design process.

Turner et al. (2001) uses visibility graph method, first introduced in De Floriani et al. (1994), for spatial analysis of architectural space. This research investigates how visual characteristics of a location are related and how this can have a potential social interpretation. The graph representation that is used incorporates isovists to derive a visibility graph of mutually visible spots in a given spatial layout (Turner, 2001). This leads to the definition of some measures that describe both local and global spatial properties that may relate to the perception of the built environment.

The literature discussed above presents research for performing visibility analysis using various methods and techniques. An issue that arises concerning the tools that result from such research is that the tools are not suitable for use by designers in practice. Most designers do not have knowledge and skills of programming, or using specialized software. This has several reasons, e.g., time pressure in a design project. Designers also don't tend to use specialized analysis software during the early design phase, because these are difficult to use, and the model usually needs to be exported and imported back and forth between the analysis and modeling software. Performing analysis on the model in the familiar modeling environment would increase the usability of these tools. Furthermore, developing the tools with their use by designers in mind would increase their usability. Our research development aims to introduce visibility analysis tools in the urban design practice.

The most recent visibility analysis methods that designers and architects use today rely heavily on computing power. Some of the well-known analysis software such as, Ecotect, Space Syntax and ArcGIS offer methods for visibility analysis. However, these

Figure 1
Analysis of visual pollution by advertisement billboards.



offer very limited methods for visibility analysis of building facades, or as we call it in this paper, analysis of 3D urban environments. In addition to that, all this software are standalone applications that do not support 3D modeling. Every new design version must be imported and analyzed in a modeling software. This approach does not support dynamic manipulation of the design model and slows down the design process. We developed a tool for visibility analysis in Grasshopper, parametric plug-in for the Rhinoceros modeling platform. Rhino is widely used among architects and designers today. Our tool can be used to analyze models directly in Rhino, and dynamic changes can be made and revised models analyzed by the tool in real time. Our tool uses a ray casting method to analyze the visibility of façade surfaces.

Our tool combines two possibilities, referring to the two quantitative methods for visibility analysis described earlier in this section: a) analysis of visibility from a given vantage point and; b) visibility analysis of a given urban setting (in particular, buildings and roads). The latter analysis provides information on the best visible buildings/building facades and segments of roads that 'see' most of the buildings.

The view pollution analysis became a first case study for the tool (Koltsova et al., 2012). An example that we analyzed is one of the pedestrian streets in the historic center of Moscow, Russia (Figure 1). Billboards and other large signs create a view pollution of building façades on this street. The definition of view pollution may be interpreted differently in different contexts. For instance, billboards and signs characterize Times Square in New York, as these form the identity of place in this context. However, on this pedestrian street in Moscow, uncontrolled placement of advertisement billboards results in a complete blocking of 18th century historic heritage buildings. Furthermore, the scene created by the signs do not contribute positively to the identity of the place, on the contrary, it diminishes the overall quality of public space.

In our current work we aim to investigate potential uses of our tool for design practice. Therefore, we established a collaboration with a practicing architect to work on a design competition together, using the 3D urban settings visibility analysis tool.

This paper elaborates on the visibility analysis methods, presents the tool in detail, and discusses the results of our joint work on the competition. We end the paper with a brief evaluation on the use of the tool by design practitioners, and directions for future work.

THE VISIBILITY ANALYSIS TOOL

This section elaborates on the functionality of the visibility analysis tool and its development process. We used Grasshopper, the parametric environment for Rhinoceros, as the development platform. In Grasshopper it is possible to write your own code in C# .NET or VB .NET and create a custom tool (or component) that performs the specific function. Such custom components require potential users (architects and urban designers) only to know what to feed in as an input (curve, points, geometry, etc.) and what the output would be. We developed two custom tools that perform the following functions: visibility analysis of building geometry, and visibility analysis of the road network (Figure 2). Visibility analysis uses a ray casting method. The algorithm requires the following inputs:

- building geometry as Breps
- terrain as a mesh surface
- road network as curves or polylines

The algorithm converts the building geometry (Breps) into a mesh. The possibility to define mesh tessellation for building and terrain surface geometry individually is embedded in the tool. This is done due to the difference in scales and analysis precisions for the two geometry types.

The road curves are selected automatically by a "Pipeline" component (Figure 2). This is the in-built Grasshopper component that allows for automatic selection of a specified type of geometry by object layer. The road network is split into segments and at intersection points. The length of every segment can be defined according to the design scale. The smaller the segment the more precise the analysis is. The mid points of segments become visibility nodes. The algorithm generates rays between mid points of the curves and mid points of mesh faces of building/terrain geometry. Then, the algorithm returns intersection points between vectors and each face's mid points and checks if there is any obstruction between the viewing point and façade surface. Depending on the result it assigns each face a color: gradient between yellow (best visible and blue – worst visible; white – non-visible) (Figure 3).

In order to save calculation time we use bounding box of building meshes at first iteration step to check for possible intersections. If generated ray intersects a bounding box then the algorithm proceeds to the analysis of the whole mesh. Intersection calculation of the ray and bounding box takes less time then ray-mesh intersection, which helps to considerably reduce calculation time.

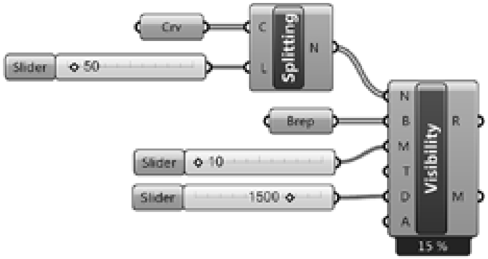


Figure 2
Custom Grasshopper component for visibility analysis. Inputs: road network (N), building geometry (B), mesh tessellation (M), terrain analysis (optional, (T)), max viewing distance (D), max view angle (A).

The main parameters that the tool uses are:

- the view distance from a view point to a façade surface,
- maximum visual angle (vertical and horizontal), and,
- angle from the view point to a façade surface.

For different design tasks specific parameters are retrieved by the tool. For example, for the analysis of city dominants (tall buildings or city monuments), the tool solely checks if the object is visible or not from a certain point or path (Figure 4a). Considering factors such as the visibility of city dominants during the design of new public spaces can improve navigation within a city. For pedestrians it is easier to choose the direction of movement if they see a dominant and know the location of it. Visual connections in the city also help to create better

Figure 3
Analysis results (best visible – yellow; non-visible – white), viewing points are distributed along the pedestrian walks with a span of 20 meters.

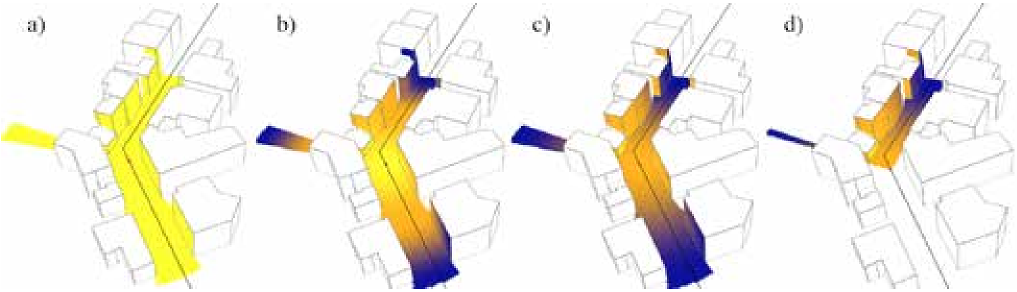


Figure 4
In red – viewing point, gradient shows the best/worst (yellow/blue) visible building facades:
a) Tool checks for visible/non visible buildings – true or false
b) Distance to façade surface is added c) Distance and angle to façade surface are added
d) Direction of pedestrian movement and its view angle is added

connected public spaces (network instead of isolated spots).

For the analysis of how detailed pedestrians can see the facades and which are the most exposed surfaces, the maximum distance and angle from a view point to façade mesh faces is added. An angle closer to 90 degrees and less distance to façade means better visibility. Gradient illustrates the best/average/worst visible façade surfaces (Figure 4b, c). For the moment the influence of distance and angle on the analysis result is 50/50. Naturally, the importance of each of the parameters can vary depending on the design task. Therefore, we plan to further evaluate the tool with architects and revise it based on their feedback. We have already added additional constraints such as the horizontal and vertical view angles to be able to analyze what a person can see while walking in a specific direction (Figure 4d). It is possible to activate or deactivate the functions described above by right-clicking the title of the component and checking/unchecking them (angle to surface, distance to surface, one direction). This is a feature that can be programmed by a tool developer in Grasshopper.

In our work we combined two types of urban analysis: visibility and accessibility. With the accessibility tool it is possible to set a starting point and analyze how far one can get by walk/car or bus within a certain time period. In this case destination points are the mid point of previously generated segments of the road network (refer to the visibility tool description before). The input parameters for this component are:

- max walking distance, or;
- time and speed by car/walk/public transport (in which case max walking distance is calculated based on these two parameters).

We use the graph component to analyze structure and create topology of the road network (Figure 5). This information in turn is used by the Dijkstra's algorithm to calculate the shortest path between starting and destination points.

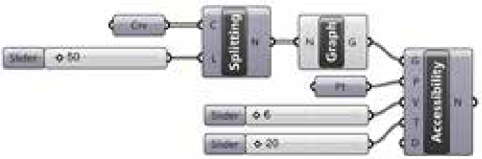


Figure 5
Custom component for accessibility analysis. Input parameters: network topology (G), starting point of movement (P), speed (V), duration/time of movement (T), max walking distance (D).

Combining the two types of analysis methods provides the possibility to analyze how far one can go within a certain time span and what one can see while walking this route (Figure 6). Figure 7(a) shows the accessibility analysis results and (b) what one can see while walking this path. The resulting path is used for the visibility analysis of best visible façade surfaces from the path. Rays are created between the road segment and building mesh faces. If a mesh face is visible from the road segment then the algorithm assigns a segment ID to the mid point of the mesh face. The more segments "see" a certain mesh face the higher the mesh face's visibility value becomes (in terms of color: yellow – best visible, blue – worst visible, white – non-visible).

Using our tool it is also possible to analyze best visible buildings. In this case the algorithm stores building IDs instead of individual mesh faces and analyzes what are the buildings that most of the road segments can "see". The same logic applies to road segments. The more buildings/mesh faces a road segment can "see" the higher visibility value (closer to yellow color) is assigned to it (Figure 7b, c).

Using the tool it is possible to analyze the visibility of a single building and the road segments that can "see it" (Figure 7d). The algorithm principle is the same, with the exception that the information of the road segment is stored as a boolean (True/False).

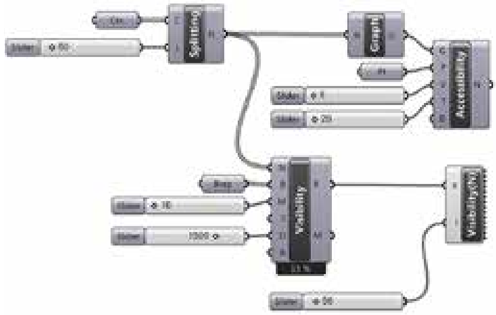


Figure 6
Combination of accessibility and visibility analysis custom components.

PRACTICAL APPLICATION OF THE TOOL

We worked with a practicing architect and applied our tools for a design competition. The brief was to develop a design proposal for the transformation of a former industrial area into a techno park. This new development is supposed to become a new local economic center and attraction point. Therefore, its visual perception from the main access points, such as bus stops, train station and highway, is an important aspect for analysis as it directly influences the accessibility and integration of the new development within the local context.

Figure 8 presents the design proposal. According to the task set by the architect the tool checked for visibility from important points around the project site (points in orange), such as bus stop, city public space and tram stop, to objects on the project site (i.e. design dominants such as conference center, old factory chimney etc.). The analysis process is shown in Figure 8, right side. The idea of the architect was to have a so called "target" matrix where he documents which elements should be seen from important view points according to his design concept (Table 1). The tool analyzes each new design scenario and creates a new matrix (Table 2). This matrix is compared to the target matrix and if there are discrepancies, building shapes are adjusted to provide better visibility. For the moment this process of changing the design based on the target matrix is manual. We are convinced this method is more intuitive for an architect and provides more control on the design process.

EVALUATION

During this collaborative work it was important for us to understand what the challenges are that prevent architects from using parametric tools and what should be changed (in the design process/tool functionality) to integrate these better into the design practice. We have conducted an interview with our partner where we obtained his opinion about the general situation and about using our tool in particular. In general, the use of tools depends on the size of the office and the scale of the projects in this office. In Switzerland, rapid urban expansion was not such a dominant issue until recently. People do not yet feel the influence of it on their lives, therefore, there are not that many design offices that deal with such challenges, and consequently, have a need to upgrade their processes or tools. Another, quite a straightforward reason, is that people are used to certain software and associated processes that they establish in their offices and as there is no immediate need, they don't want to change anything (or have time to change the routine). "As long as it works, its fine".

The architect that we have been working with is one of the few whose office deals mostly with urban design projects. He works mainly using traditional approaches when designing, which are usually sufficient. However, he remarks that the parametric approach is sophisticated, because it helps to resolve many different challenges by allowing the architect to systematically explore on a few issues at a time. His feedback on our tool was that this tool becomes

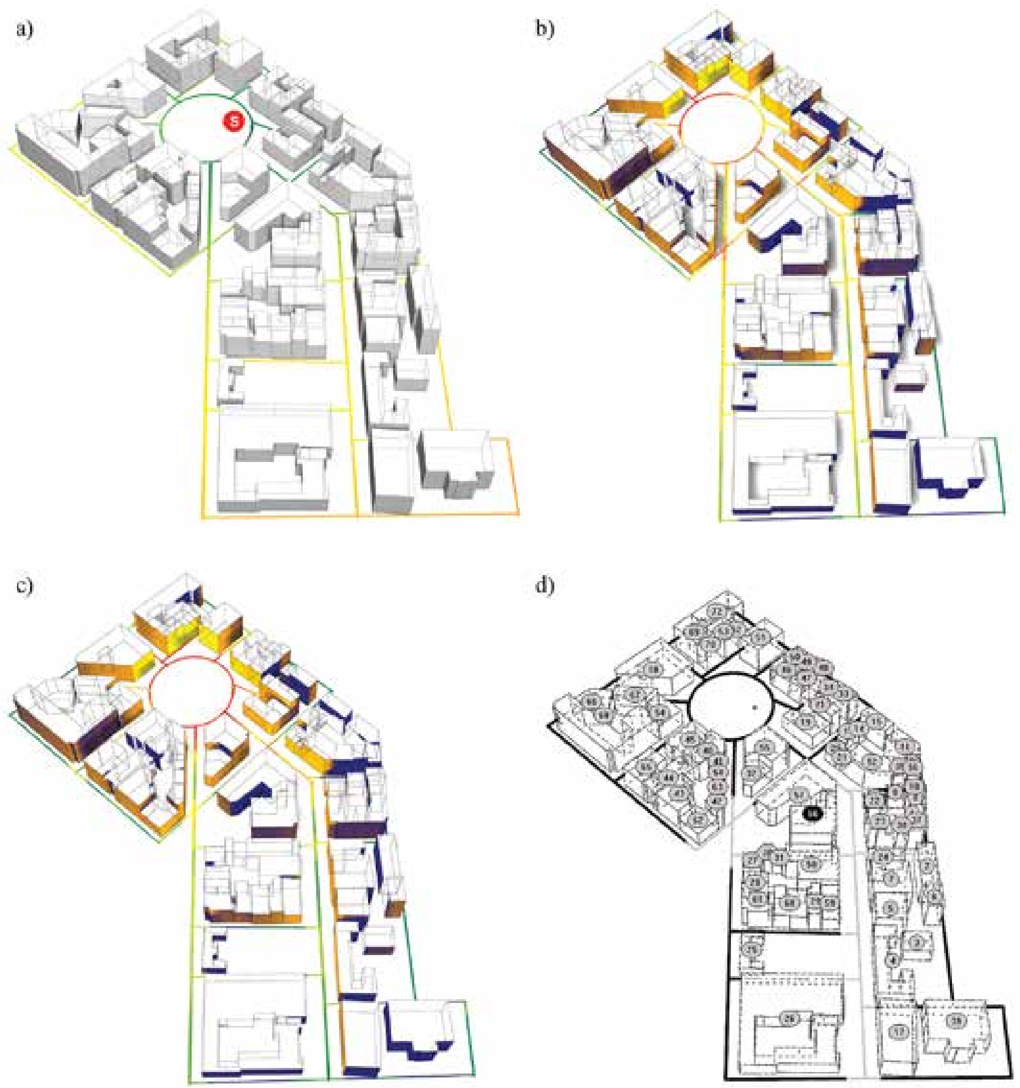


Figure 7
a) Accessibility by walk within 15 minutes, b) Visibility – what one can see walking 15 minutes, and most visible buildings (from all the analyzed visibility points) and road segments that "see" most of the buildings, c) Most exposed façade surfaces and road segments that "see" the most of the surfaces, d) Building with index number 56 is analyzed, in gray road segments that can "see' the building, black – not.

really useful as soon as the 3rd dimension comes into play. Architects are trained and can estimate what a person can see on the plan. However, when elements of context such as a complicated terrain with high-density developments are a part of design project, then it becomes quite hard to estimate the visual impact of the new design and its perception from different city locations. In his opinion, our tool can be used for the projects with, as he called it, "multiple levels and dimensions". Based on the feed-

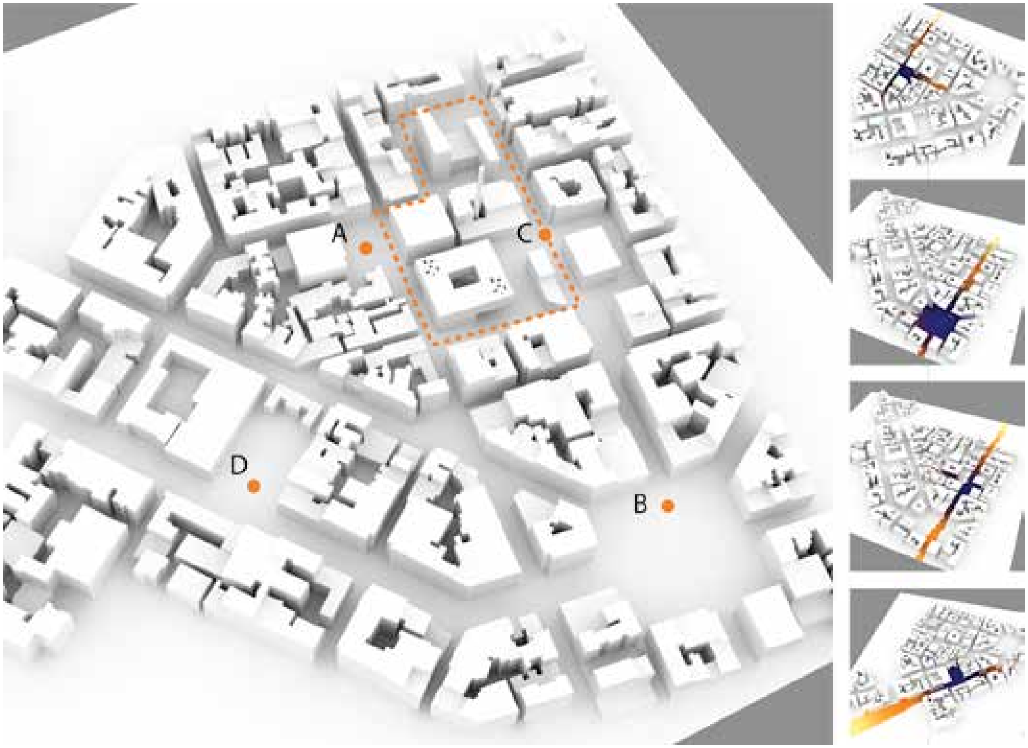


Figure 8
Top: project site and design proposal; right: visibility analysis from strategic points (street view, tram stop, bus stop, point in the city)

back we introduced additional function that allows for terrain surface visibility analysis. The meshing of the terrain surface can be controlled individually due to the scale difference and analysis precision of the two geometry types (Breps – buildings, and surface - terrain). The parametric nature of the model allows for an interactive change of the design form in order to improve the visibility.

	1 chimney	2 research lab	3 conference c.	4 admin offices	5 entrance N
A street view					
B tram stop					
C bus stop					
D point in city					

Table 1
Reference matrix.

	1 chimney	2 research lab	3 conference c.	4 admin offices	5 entrance N
A street view					
B tram stop					
C bus stop					
D point in city					

Table 2
Matrix for one design scenario.

CONCLUSIONS

This paper demonstrates the working process between a research group and a design practitioner. The application of parametric tools for design practice has the potential to establish a better communication between design theory and practice, and improve the quality of future urban spaces through better informed design processes. We will proceed with collaborative work with architects in order to enhance our methods and adapt them to the needs of the design practice.

In our future work we also plan to enhance the functionality of the presented tool by introducing additional inputs based on architects' feedback. For example, it is important to consider in the analysis the type of urban space and the type of movement it implies. In more specific terms, square/piazza or a shopping street implies lingering. The road between the transportation hub and business district would most probably have linear/directional type of movement. The perception of space by pedestrians largely depends on these factors and we will work on the ways to introduce this information into our parametric tools which would result in more accurate results.

ACKNOWLEDGEMENTS

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Human Activity Modelling Performed by Means of Use Process Ontologies

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Abstract. *Quality, according to Pirsig's universal statements, does not belong to the object itself, nor to the subject itself, but to both and to their interactions. In architecture it is terribly true as we have a Building Object and Users that interact with it.*
The problem we approach here, renouncing at the impossible task of modelling the actor's "libero arbitrio", focuses on defining a set of occurrences, which dynamically happen in the built environment. If organized in a proper way, use process knowledge allows planners/designers to represent usage scenario, predicting activity inconsistencies and evaluating the building performance in terms of user experience.
With the aim of improving both, the quality of buildings and the user experience, this research explores a method for linking process and product ontologies, formalized to support logic synchronization between software for planning functional activities and software for authoring design of infrastructures.
Keywords. *Design knowledge modelling; process ontology; knowledge management.*

AEC INDUSTRY AND INFORMATION MODELS

The approach / methodology called Product Information Modelling (PIM), historically consolidated throughout the industrial world, is typical of serial systems. In the last decades, the PIM has proven its robustness and effectiveness even in the most complex areas, characterized by the uniqueness of the product, such as automotive, aero-spatial, etc..

Its final object, towards which this PIM production system, is realised by means of a unique process, characterized by low seriality. In the last decades, this production system revealed their experimentations to be successful with repeatable, optimizable and personal solution, the so-called mass customization.

The PIM operates by manufacturing prototype products and then contextualizing its instances through the re-modulation of its structural general "core" adjusting it with little variations relevant to specific production requirements.

Through a slow process of technological transfer, still in early stages, PIM was introduced about ten years ago in the AEC industry, starting the so-called Building Information Modelling (BIM).

Well known peculiarities of AEC industry constitutes an important challenge for BIM approach, which in turn is a method / tool able to innovate this sector - central to the European economy - especially in a time of crisis like the current one.

In many European countries, governments pushed an industrial policy based on BIM, because the crisis in the sector has not only a financial nature, but, especially, an industrial nature. Moreover inefficiencies of property and infrastructure investments affect the public finances, even if current spending is much more relevant.

Through BIM which is accompanied by a more efficient information management, the sector may acquire a production quality typical of more mature industries.

The efforts of the community identified as International Alliance for Interoperability (IAI), established by scientific communities in partnership with key players in the commercial sector, in the last 10 years aimed at establishing BIM standards for the use of object technology in construction and facilities management.

These standards, known as Industry Foundation Classes (IFC) are now contained within the most comprehensive model of design, construction and Facility Management information yet created. All the main software developers in this industry segment worldwide are committed to producing IFC-compliant software.

Studying the IFCs structure, we can observe that they have been developed by means of a space-components product approach, successful in terms of data exchange and information interoperability between programs, not intended for human understanding. This lack of semantics is reflected in the modelled buildings, once it is required to simulate its behaviour in terms of usage, safety and comfort.

More specifically, to predict human behaviour in a building during its usage, by means of the actual standards, tools and technologies is an urgent open problem which challenges knowledge engineers and building designers since long time. As well it involves a lot of resources in terms of industrial research and developments in the fields of army and videogames.

FUNCTIONAL PROGRAM VS. BUILDING PRODUCT DESIGN

A shared goal, typical of all AEC industry products, is to functionally facilitate its direct and indirect users' activities, being aesthetically pleasing (Fioravanti et al., 2011a, p. 185).

In order to get this overall performance, buildings and cities behaviour has to meet various technical and non-technical requirements (physical as well as psychological) placed upon them by owners, users and society at large.

Research in this field will be seeking to reduce the gap between technology and society, to increase the quality of building production, by means of open and participatory approach.

In terms of technological solutions, the product knowledge has been fairly studied and a number of modelling techniques have been developed. Most of them are tailored to specific products or specific aspects of the design activities.

Current research on AEC product modelling can be classified in two main categories:

- geometric modelling, used mainly for supporting detailed design, and
- knowledge modelling, aimed at supporting conceptual aspects of designs.

Specifically, on the need to govern the symbiosis between building and its functions, so that computers can support every phase of construction (e.g. Solibri program), it is necessary to have information models based on an adequate knowledge representation, formally computable.

This kind of knowledge, oriented to solve complex technical problems, cannot avoid to qualify the product building through its relationship with the context and with the actors.

In terms of social contributions, on the other side, we need to clarify roles and identify responsibilities of actors involved along the building life cycle, starting from the client, through designers, providing for the participation of users from the early stages of design concepts.

The BIM methodology assumes that there is a client able to schedule formally a process of briefing, design, production and management, for example using "template" for the programming of functions and activities, and thus reducing the level of ambiguity in the requirements definition.

Client, especially if they must also manage the constructed facility, are the largest beneficiary of the process-product models development, because of their risk-based reasoning approach drives the optimization of contract management.

Designers, challenged to become more aware of product and process models, are the key to the spread and development of the most advanced information systems. An open area of research works on the interface between designer and tool, to enable the first to clearly face pre-defined patterns and then customize them while using the software they are familiar with.

Users, generally, as well known, play the central role in Architecture. The problem we approach here, renouncing at the impossible task of modelling the actor's "libero arbitrio", free unpredictable will, focuses on defining a set of occurrences that dynamically happen in the built environment.

Planners' traditional approach consists in entering planned processes (expertise, technical regulations, best practices, etc.), in an architectural schema (Wurzer, 2009; Wurzer et al., 2010). However, those processes are correct only if the planner can correctly anticipate and inform the usage of the building by different building user groups.

If organized in a proper way, it is possible to represent usage scenario, predicting activity inconsistencies and evaluating the performance of the building in terms of user experience.

At the same time it is possible to design a building use programme if it can be re-modelled during the building design process.

With the aim of improving the quality of user experience, this paper explores a method based on process-product knowledge, formalized to support logic synchronization between the planning of activities and design of infrastructures

STATE OF THE ART IN META-PROCESS MODELLING RESEARCH

Many applications use process information, including production scheduling, process planning, workflow, business process reengineering, simulation, process realization, process modelling, and project management.

There are at least two problems with the way all applications typically represent process information:

- They use their own internal representations, therefore communication between them, a growing need for industry, is nearly impossible without some kind of translator.
- The meaning of the representation is captured informally, in documentation and example, so little automated assistance can be given to the process designer.

In terms of Process Knowledge Modelling, at the state of the art, it is important to refer to some ongoing researches at the international level.

NIST CPM

A design repository project at NIST attempts to model three fundamental facets of an artifact representation: the physical layout of the artifact (form), an indication of the overall effect that the artifact creates (function), and a causal account of the operation of the artifact (behaviour).

The NIST Core Product Model (CPM) has been developed to unify and integrate product or assembly information [1]. The CPM provides a base-level product model that is: not tied to any vendor software; open; non-proprietary; expandable; independent of any one product development process; capable of capturing the engineering context that is most commonly shared in product development activities. The entity-relationship data model influences the model heavily; accordingly, it consists of two sets of classes, called object and relationship, equivalent to the UML class and association class, respectively.

The buildingSMART

Standard for processes (formerly known as the Information Delivery Manual or IDM [2]) specifies when certain types of information are required during the construction of a project or the operation of a built asset. It also provides detailed specifications of the information that a particular user (architect, building service engineer, etc.) needs to have at a point in time and groups together information that is needed in associated activities: cost assessment, volume of materials and job scheduling are natural partners. Thus the buildingSMART standard for proces offers a common understanding for all the parties: when to exchange information and exactly what is needed.

The linked Model View Definition (MVD) turns the prerequisites and outcomes of the processes for information exchange into a formal statement. Software developers can take the standard and specific Model View Definitions that derive from it and incorporate them into their applications [3]. The detailed information for this is described in the ISO standard: ISO 29481-1:2010 Building information modelling -- Information delivery manual -- Part 1: Methodology and format.

ISO 29481-1:2010 specifies a methodology and format for the development of an Information Delivery Manual (IDM). ISO 29481-1:2010 specifies a methodology that unites the flow of construction processes with the specification of the information required by this flow, a form in which the information should be specified, and an appropriate way to map and describe the information processes within a construction life cycle.

ASTM Standard Scales

The ASTM standard scales provide a broad-brush, macro level method, appropriate for strategic, overall decision-making [4]. The scales deal with both demand (occupant requirements) and supply (serviceability of buildings) (McGregor and Then, 1999). They can be used at any time, not just at the start point of a project. In particular, they can be used as part of portfolio management to provide a unit of information for the asset management plan, on the one hand, and for the roll-up of requirements of the business unit, on the other. The ASTM standard scales include two matched, multiple-choice questionnaires and levels. One questionnaire is used for setting workplace requirements for functionality and quality. It describes customer needs—demand—in everyday language, as the core of front-end planning. The other, matching questionnaire is used for assessing the capability of a building to meet those levels of need, which is its serviceability. It rates facilities—supply—in performance language as a first step toward an outline performance specification.

A set of tools was designed to bridge between "functional programs" written in user language on the one side and "outline specifications and evaluations" written in technical performance language on the other. Although it is a standardized approach, it can easily be adapted and tailored to reflect the particular needs of a specific organization.

Limits

Building Modelling is not an objective process, but rather subjective, aimed at very specific purposes that depend, first and foremost, on contractual typology. On process models there are a lot of misleading quarrels, in the sense that many models have always appeared very reductionist and simplistic in relation to the complexity of the real and the articulation of the reasons of the different actors involved.

Typically, in architecture, when a product design falls, analysts want to insert a design process to fix the bad design. However, a one-size-fits-all design process does not exist. Experience teaches that it is quite hard to force a fixed process on a design team that every actor must follow. Every designer has their own unique way of solving design problems.

Design domain experts, usually, argue that bad product design is fixed by hiring good designers not by adopting a better design process.

There is a need to produce not more models, but environments where it is more easily possible to reformulate the existing process-product models.

Specifically, process models influence the Information Modelling much more than drafting based methods. Each actor instinctively wants to rearrange the software built-in model, because a single information model cannot meet all the Requirement.

To set up an information modelling process since briefing phase, implies reasoning primarily on the building functions and on the physical environmental solutions, such as energy modelling or usage planning.

USE PROCESS KNOWLEDGE MODELLING

To provide a reliable, comprehensive and up-to-date knowledge base on use process, we thought of relying on a general structure for knowledge representation already presented and discussed among the scientific community by this research group (Carrara et al., 2009; Fioravanti et al., 2011a; 2011b), and working to extend its application field to this specific purpose.

This general process representation model is linked to a specific Building Knowledge Model (BKM) structure, oriented to formalization and description of each entities composing design product (spaces, building components, furniture, equipments, etc.).

Each entity is represented in its main features and in its relations with other entities by means of the 'knowledge template (Carrara et al., 2009) based on the already discussed "Meaning-Properties-Rules" structure.

Starting from this representation model, already applied to represent building design products, the new challenge is to extend it to the representation and evaluation of spatial and technological requirements defined according to user needs.

Specifically, the interdisciplinary processes which BKM aims to support include the following:

- Design of Use Functional Program to be performed in an existing infrastructure;
- Design of an infrastructure in accordance with a defined Use Functional Program;
- Design of an infrastructural renovation in accordance with a defined Use Functional Program and / or rescheduling of activities defined by Use Functional Program on the basis of the existing infrastructure.

Tetrahedron Of Knowledge

Scenario in which a building project is delineated by means of the outlines and guidelines is marked by four 'poles' of a Knowledge symbolic *Tetrahedron* that represent the different kinds of knowledge: product, context, actors and procedures (Fioravanti et al., 2011b).

The four 'poles' of knowledge shape what happens during the AEC design. Each 'pole' is constituted by knowledge-based system in its respective domain. In particular on the knowledge of the product (building - with its components and its multidisciplinary aspects), context (site - with reference to physical, legal, planning, ecological and climatological aspects), the actors involved (humans - professionals, contractors, customers and non-humans - agents, intelligent assistants) and procedures that regulate this process (such as commitment, design phases, economic and financial aspects, administrative and organizational rules). All these 'poles' evolve in time.

This Research Group (RG) has structured and formalized product knowledge, through a logic decomposition of the building organism. "Product ontologies" were implemented, starting from IFC standards and developing a method for explicitly modelling the rules that qualify the intrinsic meaning at different levels of aggregation.

The RG approached has structured and formalized context knowledge, both physical-environmental and jurisdictive, implementing with the same method the "Context ontology ", allowing for ad hoc support during decision-making processes of architectural product design-programming.

In the last few years RG has been studying the "Actors ontology", approaching the problems related both to modelling specialist profiles involved in the design-programming process, and profiles involved in the process of use. Some rules governing the objective part of user behaviour have been identified.

This paper reports on early results of a study which explores a method for structuring "Process ontology". The backbone lemma of this tetrahedron "knowledge realm" is the recognition of the dynamic dimension that characterizes every process model.

"Tetrahedron of knowledge" finds its most complete application in real AEC problems because, unlike the existing knowledge structures, allows actors to dynamically model process-product structures, with explicit semantics.

The BKM system based on the tetrahedral knowledge structure, enables actors to intervene in the course of work on the definition of process entities and rules. The system supports the re-modulation of the constraints and objectives of the process that are bi-univocally related to functional and behavioural properties of the product.

"Situatedness" of development processes is a key issue in both the software engineering and the method engineering communities, as there is a strong felt need for process prescriptions to be adapted to the situation at hand.

Specifically, the formalization of Use Process Ontology, qualifies and is qualified through rigorously structured relationship with the product-context-user ontologies.

To model use process entities and rules means governing the integration between product form, function and behaviour and vice versa.

Use Process Design Knowledge

Use Process Knowledge is represented by means of Use Process Ontology, a structure based on Use Process Entities, qualified by a system of Use Process Rules. On one hand these process rules govern activities planning and on the other hand they control relationship with the rest of knowledge realms: who does what, where, when and how.

Use Process Knowledge can be described by means of process classes, at different levels of aggregation:

Use Process Actions: elementary class entities structuring the Use Process Ontology. They represent the process based on user's minimum ergonomic function.

Use Process Activities: a set of Use Process Actions structured in time and space, oriented by the functional programme. They qualify the relation between users and building (spaces, components, facilities, equipment, etc.)

Use Process Rationale: aggregation of Use Process Design Activities. The importance of representation for use rationale has been recognized but it is a more complex issue that extends beyond artifact function. It is function of social-economical-environmental sustainability. (The Design Structure Matrix (DSM) has been used for modelling design process (activities) and some related research efforts have been conducted. For example, a web-based prototype system for modelling the product development process using a multi-tiered DSM is developed at MIT. However, few research endeavours have been found on design rationale (Peña-Mora et al., 1993)

Events: particular process entities, "milestones" that occur in the dynamics of the activities. Emergencies necessary to structure the causal and dependency relationship between Use Process entities.

Use Process Requirements, Performance, Behaviour

From a computational point of view, use process requirements can be defined as variables, because they establish a mapping between a set of process entities and a set of values which express some of their qualitative (and quantitative) aspects.

The specific values that satisfy a particular use process requirement in a particular situation (context and objective dependent) can be defined as use process performance.

The set of all use requirements and performances can be defined as the behaviour of the represented process entity/class in terms of use.

Design Goals Knowledge Structure

Design process goals can be stated as desirables performance measures of the sought solution. Alternatively they can be stated as set of constraints that the proposed solution must satisfy.

Each constraint indicates the specific level of performance a design solution should achieve in a particular category or an acceptable range of performance values.

It can be represented formally using this general annotation:

constraint (value | range)

where the vertical bar stands for 'or'. A constraint can be stated in terms of a specific value it must satisfy or a range of values.

The function of the goals is thus to group a number of related constraints that should all be satisfied together (Carrara and Fioravanti, 2003). More formally, goals can be represented by this general notation:

goal ({ goal } | { constraint })

This definition is recursive: a goal can be stated in terms of constraints, or in terms of goals. There is no inherent difference between goals and constraints. Rather, they form a hierarchical structure where terminal nodes represent constraints and intermediate nodes represent goals.

The conditions under which a constraint is considered satisfied must be established and eventually modified during the design process by the actors, according to the internal and external requirements.

LOGICAL IMPLEMENTATION PATH

The implementation pipeline, is oriented to predict and evaluate the performance of a building based on (planned or to be re-planned) usage scenarios and vice versa modelling scenarios of use in a (existing or to be renewed) building.

This work focuses on a multi-model view of process modelling which supports this dynamicity. The approach builds beside the BKM product representation (geometric and non-geometric), a BKM process representation.

Since BKM provides a semantic structure and a standard language (XML, OWL) what we are working on is the implementation of a bidirectional synchronization between software for Programming and software for Authoring space solutions.

The assumption of this process modelling approach is that process prescriptions should be selected according to the actual situation at hand, i.e. dynamically in the course of the process.

To implement this process, the proposed Building Knowledge Model, a formalized extension of actual Building Information Models, includes representation of both the characteristic of the ontology entity and the constraints. By means of Protégé, an ontology editor, we implemented some representative use process design requirements on top of some building ontology entities.

Knowledge Representation allows queries and constraint-verifications by means of proper reasoner and rule formalizations. In order to interrogate Design Solutions, Ontology Rules have been implemented in SWRL and tested on prototype instances of developed Ontology Classes to check use process - product constraints:

- Space configuration and topological relationships among spaces;
- Furniture and equipment dotation for each building unit;
- MEP system, Structural elements and Space configuration compatibility.

In this specific case of study, the process representation is oriented to the use programming and designing, so as to match the Activity Program, defined by means of traditional project management software, together with the design solution of space configuration.

By means of BKM general knowledge structure, it is possible to connect a labelled graph of intentions, called strategy map, as well as its associated flowchart guidelines to layout solutions.

It has been implemented a critical path diagram of Hospital operating room renovation, and now we are working on the actual link to Process Activities Gantt chart. This map is a navigational structure which supports the dynamic selection of the intention to be achieved next and the appropriate strategy to achieve it.

A set of task guidelines, intended to help in the operationalisation of the selected intention, represents some basic ergonomic rules about flow of patients, staff, equipment and material.

Once accomplished the task of formally representing Use Process and Product Knowledge according to the BKM Knowledge Structure, the implementation steps are namely (Figure 1):

1. Connect Product Design Ontologies and Use Process Ontologies (e.g. expressed in OWL language by means of ontology editors, e.g. Protégé);
2. Connect Use Process Ontologies with actual BIM, or IFC (by means of API, or using Beetz et al. (2006; 2010) transcription of IFC in OWL language);

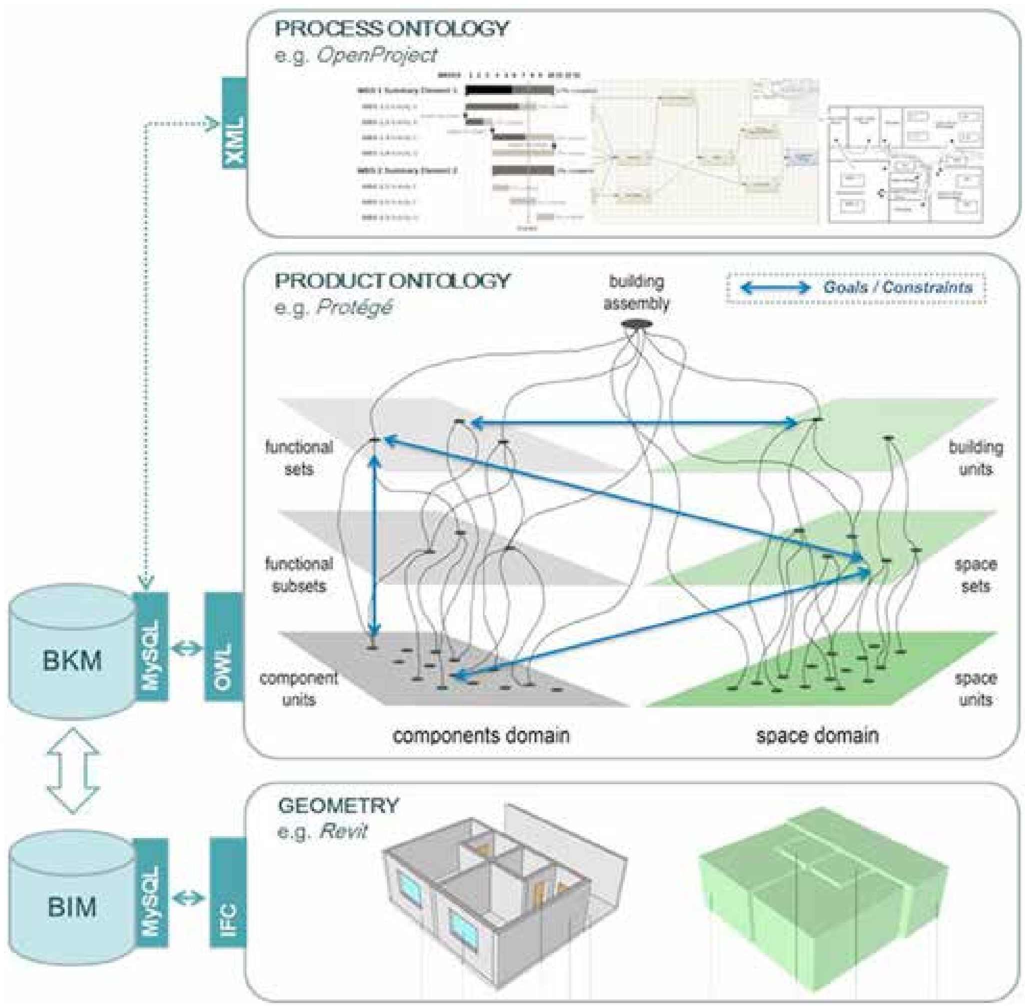

Figure 1
Building Entities and Goals Knowledge Modelling.

3. Connect BIM + BKM with a Process Management environment (e.g. OpenProject, etc.).

In order to connect the modeled knowledge with graphics in CAD / BIM, technologies related to databases definition have been used. Specifically:

- BKM ontological structure has been exported to a query-able database,
- Autodesk Revit has been selected for CAD/BIM software,
- by means of Revit DB Link (an Autodesk Revit add-in) it has been possible to export the BIM model to a database (also edit-able and query-able).

A proper database has been defined in order to ensure consistency check of the unique identifiers assigned by Revit to represented graphical entities and instances of the implemented classes in the protégé Knowledge Structure.

Similarly, this approach has been used to realize the link between OpenProject software, used to manage the XML-OWL process instances, to the Use Process Knowledge Base, in Protégé.

Revit and OpenProject represented entities are associated to instances of the BKM Knowledge Structure; data associated to entity Properties can be "extracted" from the BIM model while other features can be manually specified in Protégé according to the implemented Knowledge Representation Structure.

Linking the database allows keeping consistency between IDs from the two different environments referring to the same represented concept.

CONCLUSIONS

There is an urgent need for tools able to link and translate business rules and programme-project processes to check where business processes are not following policies and rules.

A benefit of the proposed knowledge representation is to provide automated assistance for process development by defining the semantics of process entities in a computer-manipulable way. For example, many businesses have rules, policies, space-activity requirements, that their processes are supposed to follow.

However, the representation of these, typically do not enable tools to check whether they are consistent. BKM represents rules about processes in the same way as the processes themselves, and uses a formalism that supports automated reasoning.

Introducing and enhancing reasoning mechanisms it will go beyond the potential of existing commercial tools for supporting decision making activities.

The proposed knowledge-based system supports process traceability and, consequently, allows responsibilities recognition and re-usable experiences collection.

The possibility to coordinate design process between different actors (including clients, final users, etc.) and to evaluate the building quality before its construction will increase the chances for the client to be satisfied and will provide more guarantees to success in terms of future efficiency and performance.

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3D Model Performance

New Methods for the Rapid Prototyping of Architectural Models

Production of detailed models with 3D printing

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Abstract. *Various Rapid Prototyping methods have been available for the production of physical architectural models for a few years. This paper highlights in particular the advantages of 3D printing for the production of detailed architectural models. In addition, the current challenges for the creation and transfer of data are explained. Furthermore, new methods are being developed in order to improve both the technical and economic boundary conditions for the application of 3DP. This makes the production of models with very detailed interior rooms possible. The internal details are made visible by dividing the complex overall model into individual models connected by means of an innovative plug-in system. Finally, two case studies are shown in which the developed methods are applied in order to implement detailed architectural models. Additional information about manufacturing time and costs of the architectural models in the two case studies is given.*
Keywords. *Architectural model, CAAD, Rapid Prototyping, 3D printing, architectural detail.*

INTRODUCTION

Various Rapid Prototyping (RP) respectively Additive Manufacturing (AM) technologies, which enable the direct implementation of 3D drafts in models, have already been available for a few years. Today the most popular technologies among these are 3D-Printing 3DP with plaster powder and Fused Layer Modelling FLM with plastic filament. A common feature of these technologies is that the models are created directly from the 3D-CAAD-data.

The physical 3D models are manufactured generatively, i.e. the models are created layer by layer by adding material (hence the name Additive Manufacturing). The application of these Rapid Prototyping technologies for the production of architectural models provides a number of advantages over the conventional model production. For example, it allows models to be created in minimum time with a greater degree of details. Furthermore, the reproduction and variation of drafts and models are also simplified considerably.

Another advantage in addition to this implementation speed is the low costs for the systems and materials used, resulting in a considerable reduction of the model costs. However, there are cur-

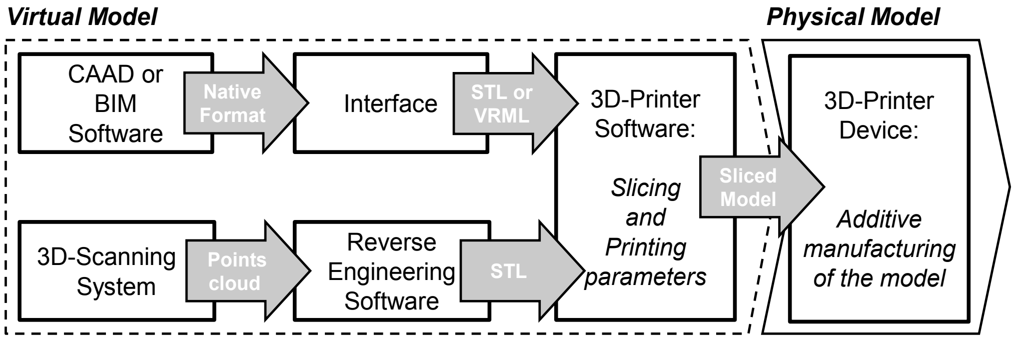

Figure 1
Data transfer from CAAD-Software or 3D-Scanning System to 3D-Printer.

rently still problems with regard to the data transfer and the preparation of the models for 3D printing, which stand in the way of further expansion of this technology (Sullivan, 2012). These problems are highlighted and dealt with in this paper.

CURRENT CHALLENGES FOR THE PROCESSING OF 3D DATA TRANSFER FOR RAPID PROTOTYPING

With all Rapid Prototyping respectively Additive Manufacturing technologies, the 3D-CAAD data are imported first and the Rapid Prototyping prepared as part of pre-processing. System-specific software is available for this purpose. The actual construction of the model in layers then takes place in a Rapid Prototyping device. Finally, the model has to be post-processed, e.g. in order to remove supporting structures or improve the stability of the model.

The 3D-CAAD data may come from different sources. On the one hand, 3D data created by means of a commercial 3D-CAAD or BIM system are usually already available for new projects. But, on the other hand, only 2D drawings are often available for existing buildings. No plans are often available for historical or even archaeological buildings. 3D scanners are often used nowadays in these cases in order to register the contours of the exterior façades and interior rooms.

The different data sources must be prepared in such a manner to allow them to be processed by the RP technologies as shown in Figure 1. In concrete terms, this means that the 3D-CAAD data have to be converted from the original file formats into a format that can be read in by the RP systems. Data based on CAAD are usually complete and consistent. However, there are still some problems with regard to the interfaces from the CAAD or BIM system to the RP software. RP devices only accept a neutral format, notably STL or VRML, but no native formats from individual commercial CAAD system manufacturers.

The simple data format STL only reproduces the surfaces of 3D objects. In doing so, the 3D object is approached with triangles, allowing the degree of detail and hence the data volume usually to be set. However, this format does not provide information on the colour or texture of surfaces, with the effect that monochrome models are created. The advantage of VRML format is the opportunity to reproduce surfaces but also coloured textures.

With data based on 3D scanners, there are usually no problems with regard to the data format, since Reverse Engineering Software often uses the STL format themselves. However, the same problem occurs time and again that the data records of point clouds by the 3D-Scanning systems are incomplete, since the scanners, which use optical sensors, find it difficult to register areas in which no light is reflected. These “shaded” areas, such as grooves and recesses, re-appear as “holes” in the data record and have to be removed with complex software operations by the use of a Reverse Engineering Software.

SPECIAL DEMANDS ON DATA FOR RAPID PROTOTYPING

Besides the data format already described, it still has to be checked whether the data are suitable for Rapid Prototyping in preparation for the construction process when processing the CAAD data. This includes, in particular, checking whether the model has a sufficient wall thickness. With a model at a scale of 1:100 or 1:200 or even smaller, it may be the case that the wall thickness of the masonry in the model does not meet the minimum requirements of the Rapid Prototyping system. It should also be checked which details are not able to be reproduced in the model.

For example, details, such as windows or banisters, are often so delicate that they are unable to be reproduced in sufficient quality by the Rapid Prototyping system, since they could break off due to their weight and fineness. Especially openings in the outer shell, such as window surfaces, skylights and doors, must be observed in particular in this respect. They are often displayed in closed condition in order to show only the exterior facade of a building. Any insights in the building or lines of sight through the building are lost in this process.

TECHNICAL AND ECONOMIC BOUNDARY CONDITIONS OF 3D PRINTING FOR THE PRODUCTION OF ARCHITECTURAL MODELS

3D printing with polymer-plaster is used and further developed in this contribution in order to overcome the previously described disadvantages for the data creation and detailing of the models. This RP technology provides several process-related advantages:

- Due to the simple printing technology, which can be compared to an ink-jet printer, the acquisition of the printer incurs only low costs, resulting, in turn, only in low hourly machine rates.
- The materials (polymer plaster, binding agent, ink and infiltrate) used is relatively inexpensive.
- Coloured models with textures and lettering are easy to produce with ink cartridges.
- Interior structures can be easily exposed with compressed air.

The economic advantages of 3D printing include the following:

- In contrast to numerous RP technologies, with this technology no additional supporting structures which have to be subsequently removed are required. In other words, only the material required to create the model is consumed. As a result, the technology goes easy on resources and is therefore sustainable (Junk and Côté, 2012).
- Overall the costs for 3D printing of models with this technology are nowadays about € 0.40/ccm. Furthermore, at approx. 23 mm/h, the construction time for a model is also relatively short (ZCorporation, 2009).

3D printing is particularly suitable for application in the field of architecture, since it is the only Rapid Prototyping technology that can be used to create coloured models. Furthermore, the model can be transferred in STL format. Since no colour information is transferred in this way, the components have to be "dyed" in the software of the 3D printer.

The second available option is the transfer in VRML format. In this case the colour information is transferred in addition to the geometry. Furthermore, additional textures, such as logos and writings, can be read in and applied in the 3D printer software.

NEW METHODS FOR THE PRODUCTION OF DETAILED ARCHITECTURAL MODELS

In order to extend the application options of 3D printing to the production of architectural models, a method has been developed to divide the buildings into individual areas. This allows very detailed models to be created, which also enable interior insights. To assemble the individual models easily without mixing them up, the Poka Joke method is also applied.

At first the building is divided into individual areas in the CAAD system. In the event of a single-family house, these sections are preferably the cel-

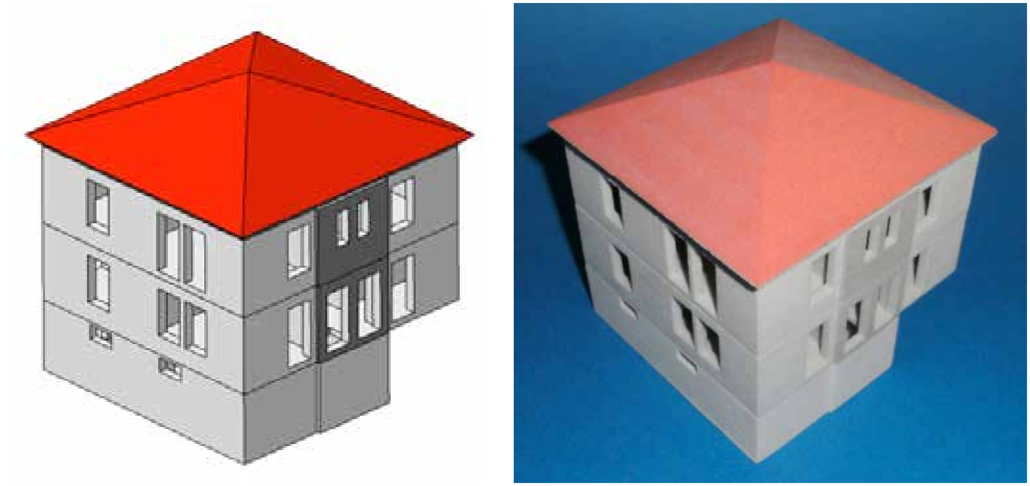

Figure 2
CAAD-Model of Single family house (left) and physical model (right), Scale 1:100.

lar, floors, the roof and adjoining buildings. Industrial buildings can be divided according to their functions, e.g. office and workshop areas, adjoining buildings, supply facilities. This gives the model a structure and allows the individual models to be designed in detail. The design usually comprises the reproduction of flooring and exterior walls. Furthermore, supporting interior walls and non-supporting lightweight walls can be reproduced. The function of the individual walls can be depicted by different wall thicknesses in the models. Interior staircases as well as pillars and supports are also reproduced.

Further details, such as windows and door openings as well as gates and skylights of industrial buildings can be integrated in the model. This allows the room layout to be recognised. Since the models are set up floor by floor and are open at the top, it is possible for the architect and customer to discuss and assess the design.

The individual models are equipped with connection elements to make it easier to handle them. They are simple plug-in connections which allow the overall model to be quickly assembled or disassembled. The Poka Yoke method is used for this purpose, i.e. the plug-in connections are positioned in such a way that there is only one way of connecting the individual models (Santos et al., 2006). This prevents the individual models from being assembled in the wrong combination. It also reduces the risk of damage due to incorrect assembly considerably.

CASE STUDY 1: SINGLE-FAMILY HOUSE

A single-family house as shown in Figure 2 was 3D-printed in this case study. The building was divided into the individual models: cellar, two living floors, roof and adjoining building.

Each floor was created with a floor plate and side walls. Furthermore, the interior walls and all openings (windows and doors) were reproduced. As needed, the functions of the rooms could be applied in the form of writings to the floor plate to provide the constructor with a better understanding. Also details like the grey painting of the oriel at the façade in the front could be demonstrated.

Since the model was created at a scale of 1:100, the interior and also exterior walls could also be reduced to the scale without falling short of the minimum requirements of the 3D printing system (see Figure 3). The individual model parts are joined by means of plug-in connections. This allows the roof and the individual floors to be raised in order to observe and assess the underlying areas. Lines of sight

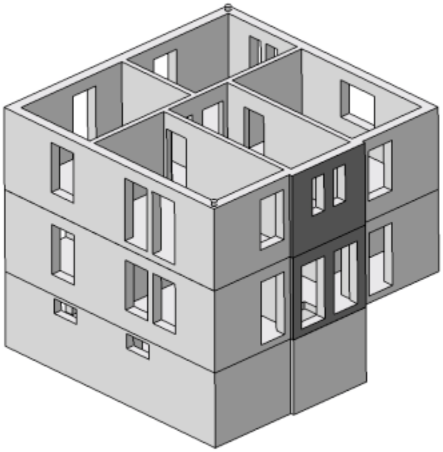
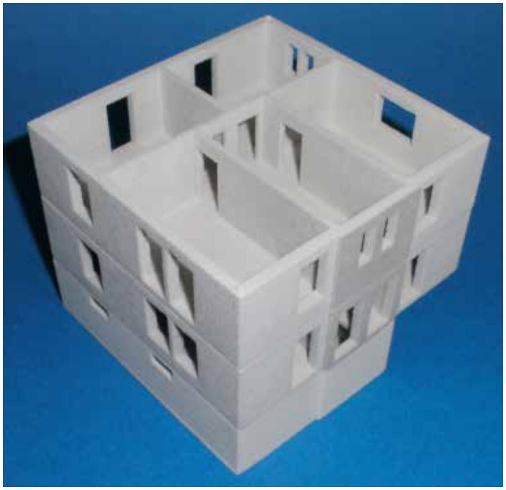

Figure 3
View on internal structures in CAAD (left) and in physical model (right), Scale 1:100.

can be seen in the building due to the open design of the building.

CASE STUDY 2: INDUSTRIAL BUILDING

The 3D printing of an industrial building is implemented in the second case study as demonstrated in Figure 4. It is used as a test centre for persons and motor vehicles. It consists of a cellar, several test halls and an office building with common rooms. The building is initially divided into storage, test, office and social function areas. However, these areas are so large that some of them need to be divided even further into floors in order to illustrate all necessary details to the constructor.

The scale 1:200 was applied to this model to allow even the largest individual model (cellar) to fit into the construction space of the 3D printer (204 mm x 253 mm x 204 mm, LxWxH). In this case, the wall thickness of the interior and exterior walls had to be adjusted (i.e. enlarged) in order to adhere to the minimum wall thickness of the 3D printer and, in this way, create a stable, durable model. As shown by the view onto the internal structure of the building in Figure 5 this distorted the scale to a certain degree, since the lengths and heights of the building are true-to-scale, but not the wall thickness.

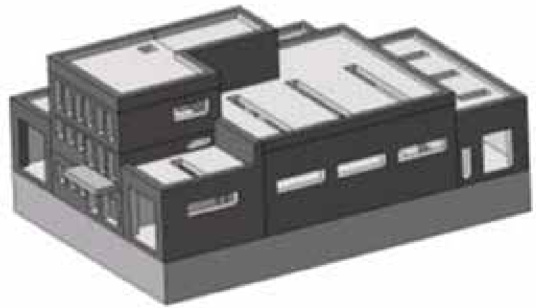


Figure 4
CAAD-Model (left) and physical model of complete industrial building (right), Scale 1:200.

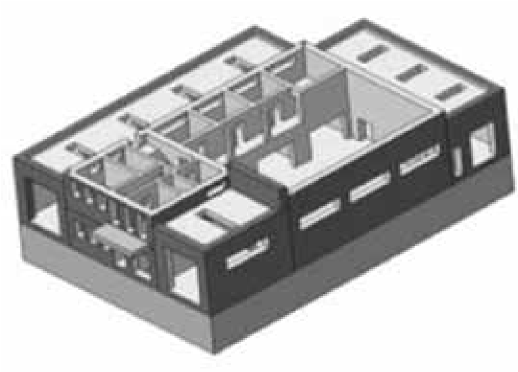

Figure 5
CAAD-Model (left) and physical model of industrial building without roof for view onto internal details (right), Scale 1:200.

The cellar, which covers all areas, serves as the basis for the overall model. The individual models are plugged onto the cellar either entirely or floor by floor. The office and common areas are particularly challenging, since they comprise numerous details.

COMPARISON OF THE MANUFACTURING TIME AND COSTS

The manufacturing times and also the costs for the two case studies are specified in Table 1. The manufacturing time is based on the actual construction time for the model and the time required for post-processing, which consists of cleaning the model to remove residual powder and the subsequent infiltration with resin. The total manufacturing time for the single-family house is considerably shorter than that for the industrial building due to the lower construction volume, the lower number of individual parts and the lower complexity of the geometry.

The single-family house is completed within a working day and can be printed, for example, overnight. In contrast, printing and reworking the industrial building is expected to take 1.5 working days, although, in this case too, printing can be performed overnight to accelerate the availability of the model. In addition it takes in both case studies some hours to maintain the preparation of the data because only 2D-drawings are available.

When comparing the manufacturing costs, a distinction must be made between material and machine costs. The material costs consist of the costs for the polymer plaster powder and binding agent used during the production phase. The costs for ink are negligible in these examples. The material costs also include the costs for the resin used during post-processing for the infiltration and hence the increase of the strength of the models. The machine costs are based on different boundary conditions (e.g. acquisition costs, service life, depreciation, interest) used to calculate the hourly machine rate. The personnel costs are not included in this calculation, since, by experience, they vary considerably.

In the both case studies the material costs of the industrial building are more than the double of the costs of the single-family-house. The machine costs of the industrial building are almost the triple of the

Manufacturing time	**Single-family House, Scale 1:100**	**Industrial Building, Scale 1:200**
Manufacturing (3D-Printing)	3 h, 2min	8h, 30 min
Post-processing (Cleaning, Infiltration)	2 h	2h, 30min
Total manufacturing time	**5h, 2 min**	**11h**

Table 1
Comparison of manufacturing time of single-family house and industrial building.

costs of the single-family house because the geometric complexity of the model. The total manufacturing costs are currently significantly higher than the literature value (ZCorporation, 2009) due to the annual price increases for materials since the publication date.

SUMMARY

The current challenges for the implementation of architectural models by means of 3D printing are illustrated in this paper. They include, in particular, the data transfer and the adaptation of data to meet the requirements of the 3D printing system. It has been demonstrated that 3D printing has a number of technical and also economic advantages in comparison to other additive manufacturing technologies.

The methods introduced for the division of the building into individual models allow numerous details to be reproduced in the exterior as well as interior. These individual models can be joined to form complex overall models using the Poka-Yoke method. Both case studies were able to show how to implement these methods successfully for a single-family house and also for a complex industrial building. The comparison of the manufacturing time and costs gives a reliable basis for the calculation of future projects.

OUTLOOK

To simplify the data exchange in future, interfaces are to be developed which simply the creation of STL data considerably. Furthermore, the printer software should be extended to make it easier to detect weak points, such as insufficient wall thicknesses, and enable the weak points to be eliminated quickly. Assistance in the division of the building into appropriate individual models would also be helpful.

For further examinations, there are plans to investigate the usage of other Additive Manufacturing technologies, such as Fused Layer Modelling FLM. This technology usually enables models of higher strength to be produced in comparison to 3DP, since plastic filament (ABS) is used as building material. However, a restriction here is that only single-coloured models can be produced. The application of multi-material printing (e.g. Multi Jet-Modelling MJM) could also be examined in order to visualise further details. This could result in a more realistic reproduction in particular of transparent details. In addition a higher accuracy of the modes is expected due to the smaller layer thickness that as used by this technology.

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Four Chairs and All the Others - Eigenchair

Data driven design

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Abstract. *By contemplating on the Eigenchair project, we ponder upon strategies and concepts of designing by using information technologies. What are the potentials of data driven design? What happens with objects when they are abstracted and reduced to a set of data? The emphasis is no longer on the creation of physical objects, but on conceiving meta-objects in the possibility space. Furthermore, this enables us to manipulate with a whole population of objects, instead of a single object. How do we get this abstract system to relate to the real world? Information technologies have opened up a number of new ways of thinking about the world and the object and they, by far, surpassed the formally simplified expression in design and architecture. Based on intellectual heritage of history and culture, information technologies can, by utilizing and recycling various elements and information, explore the 21st century object.*
Keywords. *Eigenchair; eigenvector; Principal Component Analysis; data; indexing.*

EIGENCHAIR

The project *Four Chairs and all the others* opens the possibility of an alternative definition of design. Rather than offering yet another thesis in support of linear design development, it emphasises its polysemantic nature by understanding design process as an open field of possibilities, which not only explore physical limitations of space, but also react to contemporary social and cultural phenomena. In order to explain the idea, specific techniques were used to replace simple design concepts with a series of parallel narratives, thus provoking new and unexpected situations. The primary field of interest of this project becomes the intersection of different domains of human knowledge, especially architecture, culture and information sciences.

Eigenchair is a concept that results from the effort to design a chair that refers to the genealogy of chairs, yet carries the potential of all chairs that might ever be created in future (Figure 1). This is the central subject of the project *Four Chairs and all the others - Eigenchair* which is observed and explored as a sum of ideas. Prefix *Eigen* is commonly used in linear algebra in compounds such as *eigenfunction*, *eigenstate*, *eigenvector*. It comes from the German word *eigen* which means “own”. The basic tool for the design of the population of chairs - i.e. “all the others” - is the *Principal Component Analysis* algorithm (Abdi and Williams, 2010). It is a standard tool for contemporary data analysis that has been adapted to various needs, from the neuroscience to comput-

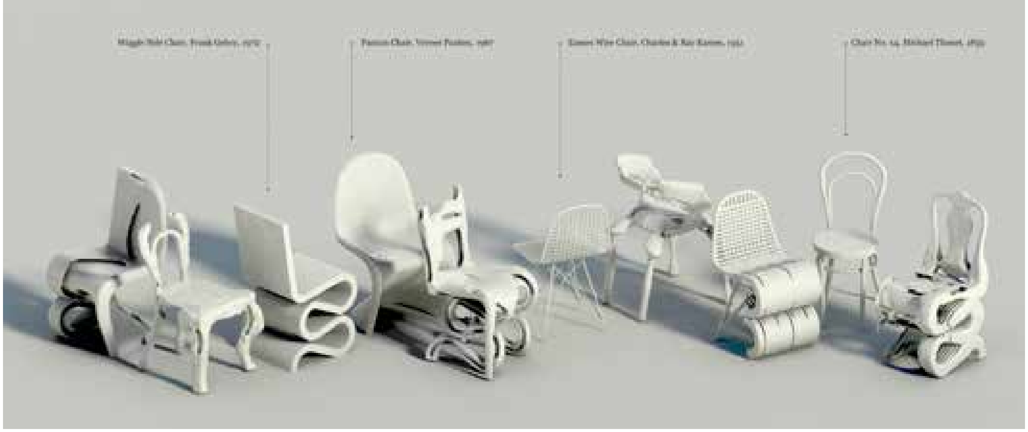

Figure 1
Different renderings of an EigenChair.

er graphics, and which is now being applied in the field of design (Sirovich and Kirby, 1987; Turk and Pentland, 1991). *Principal Component Analysis* reduces a given data set to a set of *principal components*, i.e. *eigenvectors*. The key feature of this algorithm is the intersection and interconnection of all data, whose result adapts and changes according to the required point of view, i.e. subjective interpretation.

The objective of this project is to show strategies and concepts of designing by using information technologies. What happens with objects when they are abstracted and reduced to a set of data? What are the potentials of data driven design?

ALTERNATIVE DEFINITION OF DESIGN - DESIGN APPROACH

Radical view of the world and society is today mediated through advanced technological systems. Thanks to – or perhaps due to – such circumstances, the design seeks new ways of thinking and conceptualizing, as well as producing objects and ideas. The informatization of the society and the computer-aided design are opening a whole range of new ideas about the perception of time and space we live in. The algorithmic design is now based on new parameters: design of ideas, narratives, procedures, populations, digital production, and new understanding of the materiality. Generative design methods mean creation and modification of rules and systems, which then generate an abstract machine - or a population of objects. The designer therefore does not manipulate the "artifact" itself, but rather the rules and systems which generate it. The emphasis is no longer on the creation of physical objects, but on conceiving meta-objects in the possibility space.

Recycling Information

The postmodern condition defines a set of critical, strategic and discursive practices which, as their main tools, use concepts such as *difference, repetition, simulacrum, hyperreality*, in order to destabilize modernist concepts such as *identity, linear progress of history, or unambiguity* (Aylesworth, 2013). The supermodern condition, on the other hand, is not focused on the creation or identification of the existing "truths", but on the filtration of useful information among the plenitude of new media cultural practices. In order to avoid postmodernist tautological nihilism, the supermodernist paradigm approaches the deafening cacophony of sings in an active manner. This paradigm also operates within the field of design, in which it is no longer the object that is in the focus of research, but its characteristics, features, relations, ratios, structures, indexes. The information age enables a redefinition of postmodern techniques such as *collage, assemblage or bricolage*,

Figure 2
Initial data set of 12 chairs.

all of which define an object by collecting and reassembling various information and elements. The newly created object is now a fusion of different objects' data but it is also completely unique and independent in form. This project is an example of digital recycling which, recycles information and data of chairs (Figure 2).

Elitism And Exceptionalism Of Singular Object Vs. Individual Populism Of Generic Objects

So far, the field of design understood practices which dealt with singular objects, that is, the creation of unique and specific "ideal" objects. Such an approach was closely related to the modernist paradigm. Today, however, the emphasis is moving from the design of an object to the design of an idea. The new paradigm changes designer's relation to a static object by putting an emphasis on conceptualization, interaction of the components, systems, and processes. What was once the design of a perfect, unique object featuring *specific* materiality is today the design of a population of objects featuring *any* materiality. Instead of a specific object, the designer creates an algorithm. Elitism and exceptionalism contained in the idea of a *singular* object is replaced by "individual populism" of *generic* objects. The key role is taken over by generative systems that offer methodology and theoretical world view in the framework that go beyond dynamic processes. The design process becomes an abstract definition of algorithms. Instead of focusing on a "perfect" chair a whole population of chairs was designed (Figure 3).

Imposed Materiality

In generative object design, materiality of an object is not a precondition for its final manifestation. The choice of material has so far served as the basis for determining the design process, defining the expected execution of details, connections and textures. Today, the generative system design enables the imposition of materiality to the object. The form, uncomplimentary to certain material, can now be attached to it by mere use of intellectual control. Therefore, the objects, previously described by *fixed* geometry, can now gain *relative* geometry that can be rendered into reality via 3D printing. Its materiality is the last, almost arbitrary decision done by a designer (Figure 4).

Designing Narratives

By rethinking the notion of "good design", one comes to the conclusion that design is just a tangible fragment of reality, which narrates one of the many stories that surround us. Design never appears in silence. What we call "good design" nowadays is imbued with a series of narratives constructed by different discourses: formal, ideological, psychological, and theoretical. Only one part of the design process is constituted by its material and formal as-

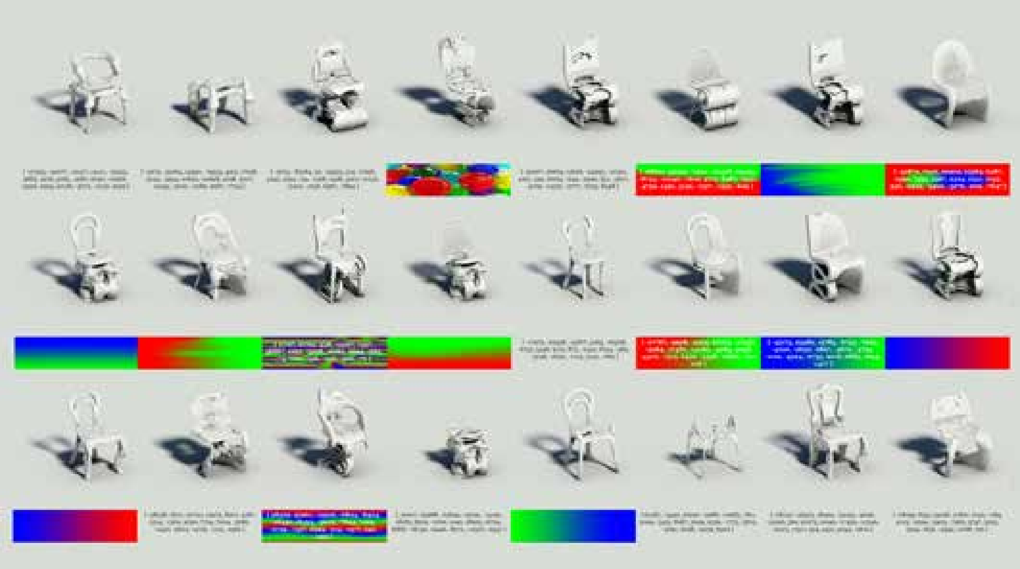

Figure 3
Population of chairs defined by maps and Eigenweights.

pects, while most of it is built upon stories which describe it and the individuals who transfer the stories or identify with them. Therefore, besides designing an object, it is also necessary to design a narrative which defines its meaning.

The research focus of the project *Four Chairs and all the others* is the design of a chair which does not carry on the heritage of iconic or functional pieces of furniture, but a one which contains information about "all chairs ever created", for which the term *Eigenchair* is used - to describe a sum of ideas. The algorithm database contains a number of "other chairs". Their fusions enable an infinite variety of possible results. In order to achieve a certain control over the results, out of "all other chairs" we have chosen four chairs as a precondition for creating identity and narrative. Fusions of characteristic parts of those four chairs with all the others are defined by user made maps that define the transformations, upgrade the performance of the *Principal Component Analysis* tool, and enable the control of the result (Figure 5). The project *Four Chairs and all the others* refers to four iconic chairs: Thonet's *Chair No.14*, *Wire Chair* by Charles and Ray Eames, *Panton Chair*, and Ghery's *Wiggle Side Chair* (Vegesack et al., 1996). Their main mutual link is specificity and uniqueness of the material and their respective technological innovation, depending on the context in which they were designed. It is the richness of meaning and historical references of these examples that are responsible for enabling us further creation of analogies, stories and narratives, which, in turn, fertilizes viewer's active participation in the process of visual representation.

MULTIDIMENSIONAL VECTOR - TECHNICAL APPROACH

The project *Four Chairs and all the others* deals with manipulating data, thereby generating new objects. A whole library of chairs, that is, their geometric and spatial characteristics, along with their historical importance and their narratives, is taken as the starting point of the project. By using open source 3D models of chairs from Google warehouse, their geometry is appropriated through a set of algorithms, after which the *Principal Component Analysis* algo-

Figure 4
3D printed models of chairs generated by EigenChair application.

rithm is used to fuse, merge and manipulate input information and create new objects. The result is a population of objects that are over coding cultural and historical space-time relations through logistic networks. Final design is entirely a product of mathematical and logical thinking. The object now becomes a product of pure intellect, grounded in history and culture. The main algorithm, which defines the whole project, is *Principal Component Analysis* algorithm.

Logical steps

The initial step was to normalize and prepare the data of all the chairs. In this case study, 12 chairs were used as testing data set due to the computational limitations. All data had to fit in the same bounding box, and mesh vertices were equally distributed throughout the mesh.

The whole application consists of three main parts. The first part is the *Algorithm for Voxelizing Polygon Meshes*. This algorithm transforms each mesh into a voxel based object defined by a one-dimensional numerical array list, i.e. multidimensional vector. In case of the highest resolution, each chair is represented with 2,788,875 values. Each value marks the distance between the given voxel and the closest mesh vertex. Values for each chair are exported as separate txt files, in order to reduce computing time of the main application (Figure 6).

The second part is the *Algorithm for Morphing Chairs*. The base of this algorithm is the *Principal Component Analysis*. The goals of *Principal Component Analysis* are to extract the most important information from the data set; compress the size of the data set by keeping only the important information; simplify the description of the data set; and analyse the structure of the observations and the variables.

Figure 5
New chair as a fusion of Panton Chair and Wiggle Side Chair.

Figure 6
Chair abstracted to a multidimensional vector.

In order to achieve these goals, *Principal Component Analysis* computes new variables, called *principal components or Eigenvectors*, which are obtained as linear combinations of the original variables. The *first principal component* is required to have the largest possible variance. The second component is computed under the constraint of being orthogonal to the first component and thus having the second largest possible variance. The other components are computed likewise (Figure 7).

According to the size of the initial bounding box, a voxel-based space is created. Each voxel receives values from txt files exported in the first step. With the use of *Principal Component Analysis* we can represent each chair by using only a set of *Eigenweights*, e.g. (-5673, -85184, 50, -25533, 31594). By changing the values of *principle components*, i.e. *Eigenweights*, we are able to achieve linear transformations between all the chairs (Figure 8).

The third part is the *Algorithm for Mapped Morphing*. It is an upgrade from linear *Principal Component Analysis* transformation to a nonlinear mapped transformation. An RGB map, in which each color represents a particular chair, is projected to the voxel-based space. This enables us to define and control the nonlinear transformations and fusions of three different chairs into a new one. Thus created, chairs can be used again as input chairs for the second step, and achieve a new nonlinear variability (Figure 9).

The rest of the algorithms served to prepare the data for *Principal Component Analysis* and to help with their final visualization. An important role was also played by a series of open source libraries, especially the *Marching Cubes Algorithm* (Lorensen and Cline, 1987), responsible for generating watertight mesh objects ready for 3D printing. All codes were written in Java programming language.

Having in mind referential and recycling discourse, it is important to note that the algorithms used in the project, e.g. *Principal Component Analysis algorithm* and *Marching Cubes Algorithm*, are already in practice. They are thoroughly adapted and functionally redirected, recycled to fit the needs of design.

ARTICULATING INDEXES - THEORETICAL APPROACH

Information

The key term which best describes and corresponds to contemporary society and science is information. Information technologies are entering all spheres of society: from the ways in which we organise our everyday life, to the ways in which we think about natural sciences and humanities. This leads to the conclusion that is impossible to understand human environment only in material terms of energy and matter; in order to create a comprehensive world view, the analysis must take into consideration the category of information. At the same time, being surrounded by excessive amount of information, the analysis requires a stable environment, which enables their observation and use.

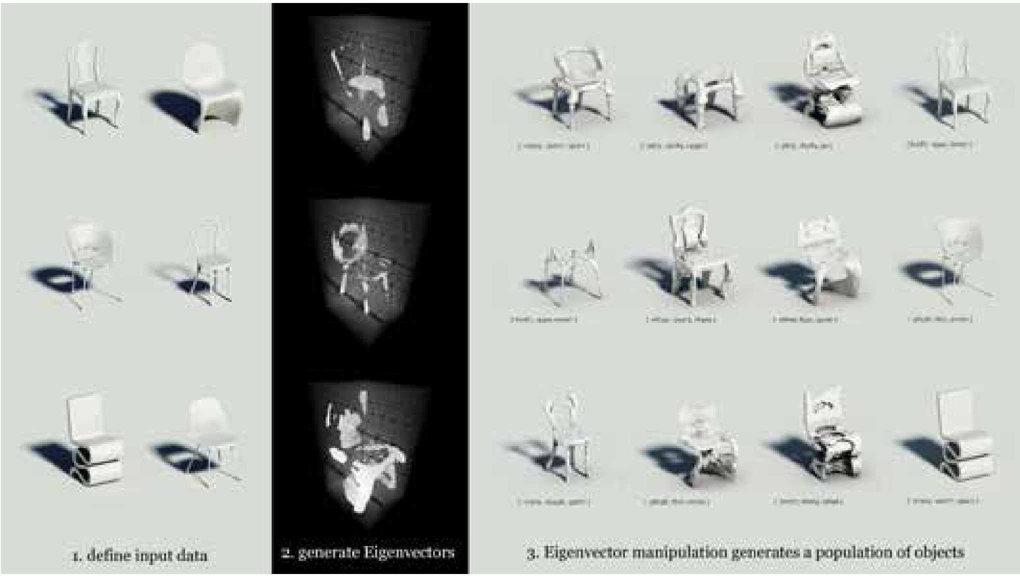

Figure 7
Workflow of the Algorithm for Morphing Chairs.

Reflection On The Real

It is impossible to comprehend or examine what is "real", because it depends on quantisation and formalisation of ideas. The hierarchy and the relation between the original and its copies, which was the key concern of the materially oriented society, have become completely irrelevant in an age in which virtual reality dominates human lives. Depending on the ways of our understanding and accepting of the "unfamiliar", we legitimatise and comprehend the real. Brian Massumi perceives this in a multifaceted way, by comparing Baudrillard's interpretation of the reality-simulation, in which there is no division between the real and the virtual, with Deluze's and Guattari's negation of the linear approach to the real. Such understanding of reality is supported by the vanishing of boundaries and the influence of the virtual on the real. *Simulation is a process that produces the real, and vice versa* (Massumi, 1987).

Figure 8
Main EigenChair application interface – left Voxel based space – right – control board.

Abstraction

The Internet age is exactly such condition, in which immaterial information is part of what we call reality. In this context, the only way of manipulating with information is abstraction, and it can be adequately used only by those who are, in a mass of information, able to define their context as a flexible, adjustable field of possibilities with multiple meanings. The project *Four Chairs and all the others* considers the abstraction of objects to the degree that enables their manipulation and the creation of new meanings (Figure 10). If objects - chairs, or whole populations of objects, are abstracted to the level of multidimensional vectors, i.e. to a series of numbers in a line - indexes, they become very potent and manipulative (Figure 11). Such abstract objects, i.e.

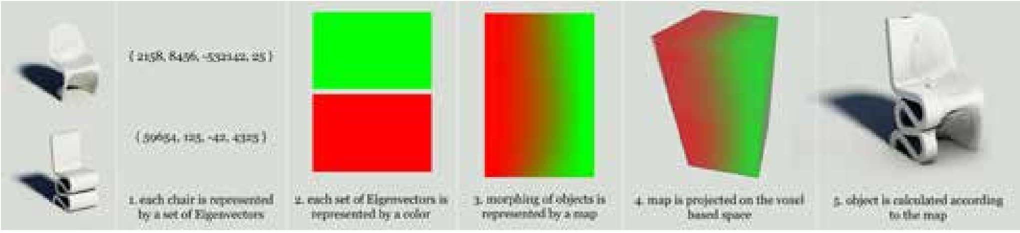

Figure 9
Diagram of an Algorithm for Mapped Morphing.

indexes, are placed in a meta-space, which contains potentials of all objects present there (Figure 12). Governed by the *Principal Component Analysis* algorithm, meta-space is able to correlate indexes of all objects, creating thus an open logistic network, a possibility space. This marks the level of articulation of different elements and the creation of whole populations of objects of the same "kind". By looking at objects through the level of their abstraction, we realise the potency of information (in meaning and shapes, with which we can manipulate), but at the same time its complete emptiness when perceived on the index level alone.

Meaning, Context And Narrative

Post-traditional society offers new perspectives on old concepts, to which we give new meanings or judge them by creating our own context. The mass of information shapes our world: text, visual representation, music, money. However, the idea that *"information does not carry meaning"* offered by the information theory pioneer Claude Shannon, has become rather liberating in the academic discourse; information carries unlimited freedom of manipulation. It is important to emphasise that contextualisation and the successive creation of narratives "fill" the systems of information. They gain power by careful selection of data implanted in them, taking care at the same time that the contextualisation and the creation of stories which surround them rely on culture and history (Figure 13). It is also important to note that in the process of contextualising the generic before the generation itself, there is a whole scale of possibilities which had been predetermined, but which are also opening the potential for the unexpected. This project shows that design is able to manipulate predetermined potentials, while filling them, at time same time, with narratives. Design is not a part of the endless evolutionary process aimed at creating the next new ideal object, but a part of a defined context and chosen references with their respective genealogies.

EIGENCHAIR - DATA DRIVEN DESIGN

By using information manipulation and various spatial conceptions, algorithmic design approaches an object in a completely abstract manner, separating it thus from the "reality". While making it extremely flexible for different interpretations and contextualisation, it also contributes to the instability of the process as a whole. The object can easily be reduced to a geometry exercise. Therefore, the key feature of design is not only the definition of algorithms, but also the construction of parallel narratives around the object. It is therefore necessary to re/turn to the postulates of the pre-Socratic philosopher Empedocles who claimed that "nothing comes out of nothing and nothing disappears into nothing". Such philosophical re/turn marks an effort to observe context and processes as more important factors for defining the object, than those implicit in the Objectiv-

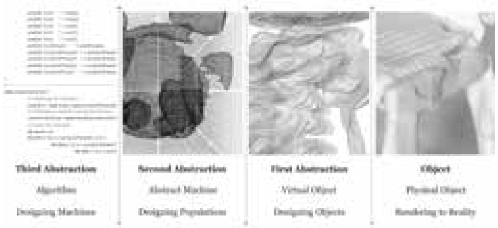

Figure 10
Levels of abstraction.

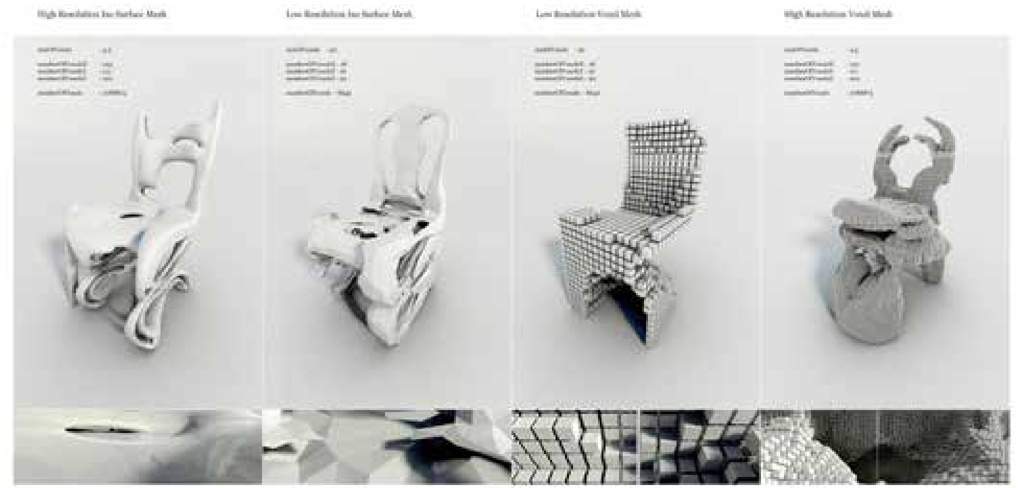

Figure 11
Different resolutions and visualization of an EigenChair

ism (Terzidis, 2012). The advantage of the processual design in contemporary world is its ability to refer to the sum of global knowledge and to use it effectively. The result of such turn/over is the creation of new perspectives in defining objects, as well as a gradual shift of design's limits. Finally, the algorithmic design should adopt strategies and dynamics which deal with the creation of narrative and contextualisation. This project tries to show – by conceiving and shaping the idea of a chair for the 21st century – the ne-

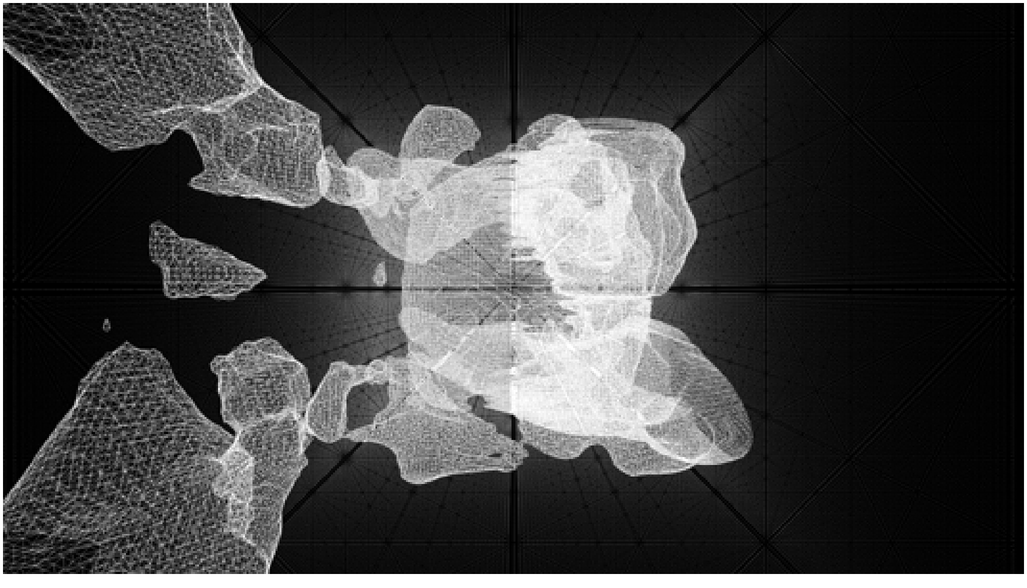

Figure 12
Meta space - possibility of interconnection and interrelation of all active data.

Figure 13
Contextualisation and the creation of stories around objects.

cessity of perceiving design through three equally important, interdependent positions: design, theory and technology. Design is now data driven.

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Digital Design Tools versus Architectural Representation and Design Approach

A reading off architectural press

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Abstract. *This study aims to investigate the relation between evolving graphic representations and due to new digital tools and how they affect architects' approach to design process. In order to do this, Yapı Magazine being published since 1973 in Turkey will be retrieved and data related to types of architectural design representation used will be recorded. The study will conclude with an evaluation of new representation means such as 3D render, other 3D digital products and diagrams and how they have influenced new approach to design.*
Keywords. *Digital design tool; architectural representation, architectural design thinking.*

INTRODUCTION

This study is interested in transformative reflections of digital design developments at two levels: architectural graphic representation and architectural stand.

The notion of "generic design" proposes that there are great similarities between design acts (Gero and Purcell. 1998) independent of the domain (Zimrig and Caine, 1994). On the contrary, there are also opinions supporting the presence of significant differences depending on design situations (Visser, 2009). Visser (2009) enhances the notion of generic design and states that there are different forms of design. He defines three dimensions as sources of differences in design consisting of the process, the designer and the artefact

Here it is hypothesized that as new tools of design are adopted, such as digital tools, a relevant shift in design stand takes place. This study aims to read this shift through a collection of architectural representations.

METHOD

This study will attempt to demonstrate a relation between the shift in graphic representation and design stand of architects in respect to architectural press, Yapı Magazine. Yapı, the oldest established magazine still in press today in Turkey, will be utilized as a tool in order to evaluate the chronological period between 1973, the year Yapı had first been published, and 2012 to understand how digital tools have affected architectural representation and approach. Yapı Magazine, as a tool to navigate through time and variety of projects, will provide evidence for claimed mutual evolution between digital design tools and architectural design approach that is proposed to be read off architectural graphic representation.

READING OFF ARCHITECTURAL PRESS

The reason for studying evolution of architectural representation due to digital technologies off of an architectural press is that these magazines publish, at least today, a variety of projects with consistency and that they reach a large amount of people. Significance of its audience is that although it refers to architects, professionals and architecture students by content, anyone can reach it. It makes information on architectural design affordable and it constructs a communication line with the people in the same field.

An architectural publishing may reflect personal views of the author or a collective view of the editors. Certain types of style may be or may not be of preference to the magazine or which aspects of a design to focus on such as detail, process, construction etc. may depend on the principles set by the editorial board. Although a magazine may be reproduced from a subjective point of view, this is a consequence of communication through any kind of medium (Sert, 2006). What is more valued here is that architectural magazines provide a record of change in terms of preferences, culture, tool and representation.

REPRESENTATION AS A REFLECTION OF THOUGHT: TOOLS HAVE SHAPED THE WAY DESIGNERS REPRESENT AND APPROACH TO DESIGN

Representation is a mean in which information is embedded. Abstraction and use of symbols are its core features through which the aimed information is communicated. It is a process in which an idea is presented in another form. In this process, information is put into related forms of conveyance.

Architectural representation acts as means of communication of those ideas embedded in design through a visual forum. In order to represent an architectural design idea, scale models, sketches, renderings, perspective drawings and photographs are used most commonly (Kalay, 2004). When communicating a design idea, representation methods that explain the project best are preferred. The intent is to convince reviewers that the design solution is the preferable one to the design problem in hand. To achieve this, the project has to speak for itself through its graphics. The core of the design idea should be able to reveal itself through the way it is represented. Sole image of the design proposed is not always enough. The reviewer needs additional graphic representations that reveal intangible information about the design to fully comprehend it. Architects produce plans, sections, elevations, scale model, diagrams, flow charts, exploded axons to make the project as explicit as possible. The difference between these representation types is defined as either yielding the "receiver o be an active participant in the communication process, or pass the idea directly to the receiver" (Kalay, 2004).

As printing technology evolved and digital design tools became ubiquitously used, they made indispensible impact on graphic representation of a design which we have previously related to reflection of design stance. In 1970's, a project was represented solely with its technical drawings such as plans, sections and elevations. However, due to technological restrictions of the time, they were far from being explanatory and acted more as technical reports. These drawings are referred to as "static" by Kalay (2004). The drawings were made by hand and there was no way of altering them so that reviewers other than the client and the contractor may be involved in the process. These representation norms have also been necessary as they are today. Today, these technical drawings are enhanced with sketches, perspectives and other graphical materials. Today, we should review the gradual change of graphic representation norms and attitudes. The hypothesis is that, graphic representation of an architectural design have become more analytical and revealing in terms of how the building will behave once it starts functioning as well as the process leading to the particular solution.

In order to support this argument, a collection of examples relevant to a 40 years span of timeline will be utilized and make this tool dependent shift in graphic representation in architectural design comprehensive. A paradigm shift from sketches to orthogonal drafted representations of design proposals are expected to evolve into photo-realistic renders, exploded axons and more descriptive diagrams regarding performative analysis, function and expected behaviour of the building and algorithms.

As Archim Menges (2010) points out, designing with digital software requires to think of design with an algebra of collections, in a more abstract way. Also architectural representation is not static as it had been; it also has transformed with regard to new ways of design approach.

In this study, architectural graphic representation is taken as a reflection of architectural design stand. Results regarding the design approach adopted will be driven through analyzing its graphic representation; and the impact of digital design tools on architectural design thinking is expected to become more rationalized as navigated towards present day on the chronologic timeline.

THE STUDY

Yapı Magazine was examined from 1973 to 2012 to investigate the change in architectural graphic representation. Three issues for each year were examined. These issues are January, May and September – so that the publishing is followed with 4 months interval for the last 39 years.

The retrieval process consists of three phases. Graphic representation means were extracted through the first phase. They are as follows: plans, section, elevations, partial details, 3D renders, 3D digital perspectives – wireframe and axonometric views, sketches, hand drawn perspectives, diagrams, physical model photographs and photographs.

In the second phase, these graphics were quantified to see how intensely they are utilized. In addition, 3D digital perspectives – wireframe and axonometric views as also referred to as other 3D digital products, and diagrams were assessed in terms of for what purposes they were used so that they may be related to possible tool developments. During he second phase of the study, the records also included project name, function of the building and the architecture group in charge in addition to information regarding year, issue and page references. This additional information may help for a deeper understanding of representational means utilized as they may vary according to function or the design team being local or international.

And in the third phase, an assessment of the nature of drawing belonging to one category during the span of 39 years were compared qualitatively to investigate how that certain types of representation have evolved in time.

RESULTS

Yapı Magazine was retrieved between 1973 and 2012. Relevant issues in 1973, 1977 to 1982, 1984 and 1986 to1987 were either could not be found or has been observed not to contain any design projects. It is almost with 1990 that design projects are published with consistency and it is after 2001 that the magazine publishes multiple design projects in each issue. According to this, a total of 155 design projects were recorded in terms of which representation types they have used.

The first phase of the study shows that plan, section, elevation, detail (construction drawings) 3D renders, 3D digital wire-frame/perspective/axonometric views, sketches, hand drawn perspectives, diagrams and physical model photographs (explanatory drawings) and photographs are used collectively with varying percentages in time.

In the second phase, as already expected, the results show that plans, sections and elevations as conventional architectural representation types are commonly used. It should be noted that actual photographs of the buildings are the most frequently used representation type. However, this was omitted in the results so that the evaluations can be made within those types of representation that are involved during the design process. Beginning with 1994, 3D renders as well as diagrams and other 3D digital products start to enhance architectural representation medium. In Figure 1, a bar is dedicated for each year. Each graphic representation type is assigned a colour and bars are segmented according

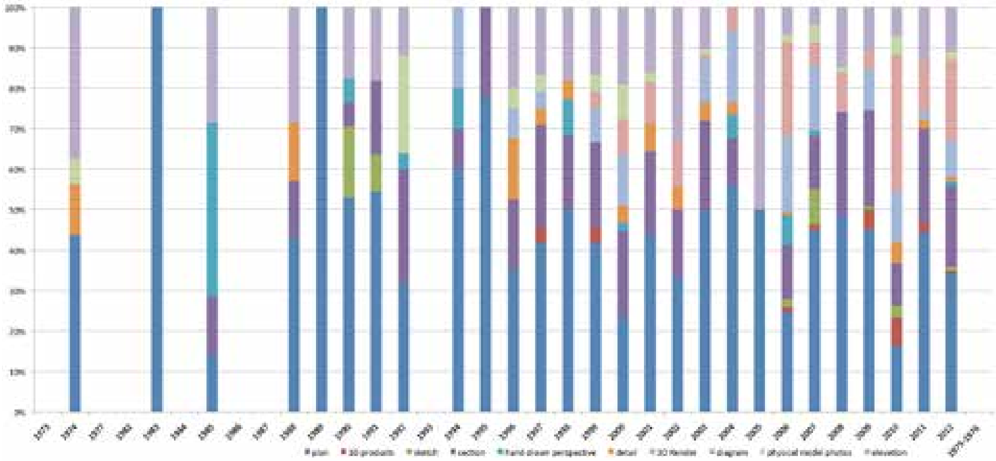


Figure 1
Distribution of Representation Types Among Years.

to their percentage of use. The increase in the variety of colours between 1973 and 2012 represents the variation in representation medium used in presenting architectural design projects (Figure 1).

As it may be read on Figure 2, first 3D render has been encountered in 1994, first 3D digital product consisting of wireframe, perspective or axonometric views with no intention regarding photo-realistic images in 1997 and first diagram is encountered in 1999. It may also be observed that use of diagrams are usually aligned with use of 3D digital products and 3D renders are always the most preferred type of representation among these three (Figure 2).

These data have also been re-interpreted in terms of by the design teams they have been produced. Expected frequency of 3D renders, other 3D digital products and diagrams have been much higher in contemporary design projects. However, since the data is acquired from a local magazine a question of whether the results may come up as expected had this study been conducted through a magazine of another nation or an international magazine. Results have shown that the number of international design teams using diagrams are triple

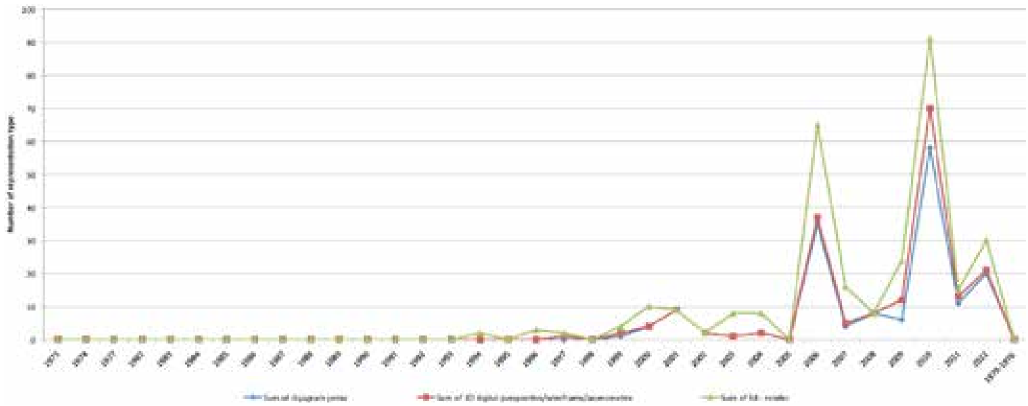
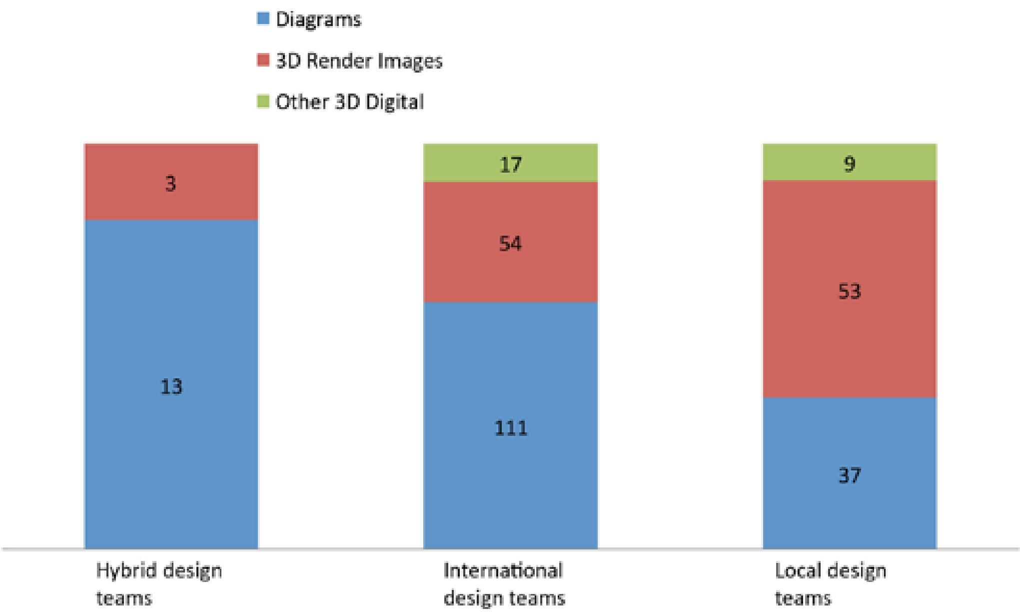


Figure 2
Beginnings of representing with 3D digital media and diagrams

Figure 3
Use of diagrams, 3d Render Images and other 3D Digital Products by Local and International Design Teams.



the number of local design teams. The number of international design team using 3D renders are almost equal to local design teams. The number of international design teams using other 3D digital products are almost double the number of local design teams utilizing these representation mediums to present their project (Figure 3).

The third phase of this study was an evaluation of qualitative features of the architectural representations. In the last years digital technology has influenced architectural representation and transmission of design ideas with new methods and tools. With new possibilities of expression in architecture, transmission of ideas has differentiated from traditional architectural representations.

In this direction, the presence of multi-disciplinary approach such as graphic techniques based on diagrams and schematic drawing, the use of abstract representations, more simple drawings even cartoonish, the presence of simple mathematical expressions can be found in architecture milieu. Previously, architectural representation was once a language that can be understood merely by architects, planners and related disciplines but now it is transformed into a language that can be understood by everyone. Even traditional representations such as plan, section and elevation have transformed into a simpler and schematic form with reduced level of detail and high level of abstraction (Figure 4 and 5).

As Kalay (2004) mentioned, main mechanism that transforms an idea into a communicable message is abstraction. Abstraction, extracts and distills the meaning of the message, focusing attention on its salient characteristics. Higher degree of abstraction makes communication more efficient and it helps to focus the receiver's attention on the parts of the message that the sender considers most important. According to the results of the third phase, simple graphical expressions, schematic drawings and diagrams become a more efficient way of representing design ideas, an ideal method of communicating ideas to others (Figure 6).

Figure 4
Evolving Representation, Plan in 1990 and 2010 (Yapi Magazine).

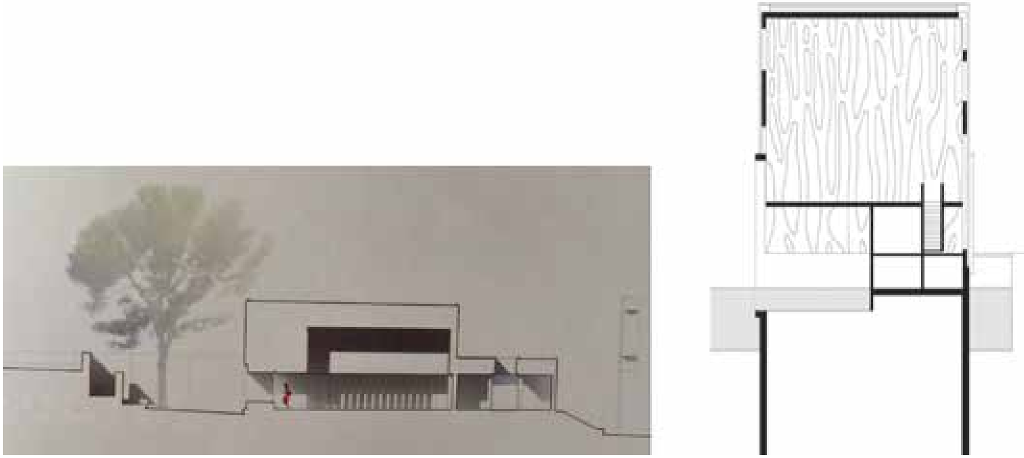


Figure 5
Evolving Representation, Elevation, Section (Yapi Magazine, 2010).

EVALUATION OF RESULTS

What Diagrams Tell

Diagrams provide a visual medium of communication for the sake of architectural representation. The most important feature of a diagram is that it has its own language that everyone can comprehend. They work across linguistic and cultural boundaries. (Kalay, 2004) Another important feature of diagrams is that they tell stories regarding the evolution of an architectural idea. They may be referred to as inclusive and dynamic. They include any viewer into the process of form in formation. Contrary to traditional ways of architectural representation, they do not

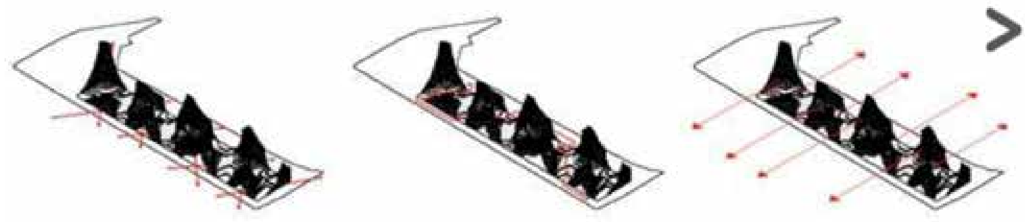


Figure 6
New Representations, Diagram, Battery Project, JDS+BIG (Yapi Magazine, 2010).

act as final reports of a process but represent the process itself. They "*explore, explain, demonstrate or clarify relationships among parts of a whole*". (Kalay, 2004) Similarly, according to Rowe (1987) diagrams are used to explore, analyze and synthesize ideas. Diagrams may be utilized to establish design principles that help the designer reflect on and prepare for subsequent exploration (Rowe 1987).

Architectural diagrams do not only represent physical elements, but also forces and flows. In the early phases of designing, architects draw diagrams and sketches to develop, explore, and communicate ideas and solutions. Design drawing is an iterative process. It involves externalizing ideas to store them and recognizing functions as well as finding new forms and integrating them into the proposal. Thus drawing is not only a vehicle for communication with others. It also helps designers understand the forms they work with (Edwards 1979; Do and Gross, 2001).

With a more thorough approach, Oxman (2000) states that diagrams play a role in visual reasoning. And through what this representation medium provides, what Schon (1992) refers to as "*reflection in action*", what Lawson (1980) describes as having a "*conversation with the drawing*" takes place and aids the design process.

What 3D Products Tell

According to Lopes (1996) due to techno cultural changes, pictures are re-emerging. They now play a role in terms of storage, manipulation and communication of information.

Beginning with 1994, 3D render images have evolved into photo-realistic images where the design proposal is presented as a finished product. This representation type is specifically chosen for presentation purposes rather than aiding design development phase. These images are used to aid those who are not architects or professionals in familiar fields but individuals who can not read construction documents.

Although this representation medium needs to be evaluated differently than diagrams and other 3D digital products, it also serves for the same purposes: inclusion and exposition. Similar to diagrams, 3D render images also tell stories. They are used to reveal how the space created during different times of the day or different days of the year. Through the photo-montages made, they give clues regarding how the spaces may be used and what kind of life will take place once its inhabited. These images are used for revealing a certain experience provisioned for designed space.

According to Bares-Brkljac (2009), these images inherit accuracy, realism and abstraction. It is through these features that non-professionals believe in what they see. According to this, accuracy aids non-professionals to be acquaintance with the space. It is related to scale, distances and relations of volumes and spaces. (Bares-Brkljac 2009) It is also related to chosen view points regarding angle and height. Human eye angles are preferred on purpose so that the viewer can imagine himself in the picture. Realism helps the viewers understand and evaluate the proposal the same way they perceive the environment. (Bares-Brkljac 2009) Abstraction refers to reduced information about design. (Bares-Brkljac 2009) A high level of abstraction may not sufficiently present the proposal where a low level of abstraction may overload an image and draw the viewer away with the information he does not need and comprehend. According to Bares-Brkljac, the collective effect of accuracy, realism and abstraction in relevance to the form, influence observer's perceptual responses.

On the other hand, Koutamanis (2000) draws attention to a cognitive property of this representation medium by stating that they act as a reinforcement of internal representation by external ones.

Why have we not encountered more?

Contrary to expectations, research areas studied in the computational design such as parametric design, scripting and building information modelling (BIM) has not taken place in the design magazine to represent design proposals yet. This may be due to similar reasons for why use of CAD tools have been slow in the 1980's. In 1980's, Jon Pittman explains the reason for slowness in computerization as the expenses of owning the machines. Koutamanis' (2000) approach also supports Pittman's. After the democratization of computer technologies domain specific systems such as drafting, modelling and computer generated images were expected to flourish. However, this process took time as well. According to Koutamanis, *"The main reason has been the understandable caution with which we approach systems that purport to improve not only efficiency but also design quality and performance."*

Although today, every design office holds sufficient amount of hardware and a more advanced software along with its know how, these offices can not afford to spend time to master even more recent software offering new methods and possible incompatibilities due to new design methods between coworkers and other professional teams. However, the authors expect to see these contemporary methods of design and their graphic representatives in architectural design magazines in the following years.

CONCLUSION

Evolution of new digital tools and new representation medium for the architectural design process has enriched the way architects represent their work. And how they represent their work is here associated with their stand and the way they think about architecture through what these new representation types offer. According to this and through the data acquired from Yapı Magazine regarding the use of representation types, this study may conclude that architects have become more process oriented, expository, transparent in terms of reflecting the design process, inclusive rather than exclusive or isolating, abstract as well as more precise in revealing experience where on the contrary it had been all about communicating the information to the contractor to build the project.

The authors had expected to encounter traces of contemporary design methods such as algorithmic design, building information modelling and parametric design. However, due to reasons explained above the expectations have not been met. The belief is that these methods still need time to penetrate into more design offices and find place in design magazines ubiquitously.

If another magazine was chosen as source, the data may come up differently due to publishing principles of the magazine. However, this approach is still seen valid since it establishes a controlled experiment by stabilizing the source and searching for evolution of new representation types among years.

Again, if another magazine was chosen with an international identity, some results may have doubled since the results of this study has shown that the number of international design teams using diagrams, 3D renders and other 3D digital products are double the number of local design teams utilizing these representation mediums to present their project

A future method to test this idea is to look at design competition entries both locally and internationally. This way, more ambitious sets of representation is expected to encounter as well as more contemporary methods of representation where architects feel encouraged to try new methods rather than to follow conventional methods of a design office.

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Considering Physicality in Digital Models

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Abstract. *This paper discusses the integration of physical and digital models in the context of building technology teaching. It showcases projects that explore the design possibilities of a chosen structural system with the use of parametric and behaviour-based computational modelling. It uses detailed mock-ups as vehicles to study, optimize, and evaluate the design as well as to provide feedback for student learning and the direction in which future designers may engage computational design. Finally, it investigates digital-to-physical design translations, the importance of which becomes more and more critical in the context of the current, computer-intensive architectural education and professional practice.*
Keywords. *BIM; building information modelling; parametric construction details; construction assemblies.*

INTRODUCTION

With digital tools firmly established in professional practice and academia, the question of the continued relevance of physical and traditional methods is often overlooked or unexamined. Certainly, there are passionate statements being formulated on both sides, with analog thinking more and more on the defensive. However there is a need for closer investigation of the analog-to-digital and digital-to-analog phase changes to further improve the development of computational tools and digitally driven creative processes.

This paper looks at the close integration of physical and digital models in design practice and investigates the ways both design environments inform each other. The goal of this paper, however, is not to justify why we need physical and traditional modes of thinking, but rather to point to needs in the further development of computational design thinking, which in many aspects is still not up to par with the traditional (not digital) design process. The intuitive, even haptic, use of tools; a natural conceptualization framework; and the lack of physical considerations are just some of the issues waiting to be addressed by the computational creative framework.

This paper specifically looks at materiality embedded in architectural models, their physically based behaviour, and the haptic feedback designer and makers receive when interacting with their products. The emerging question is what forms of digital software and interface would provide a comparative level of interactivity: what software features and design interface would facilitate full virtualization of the design process.

PHYSICAL-TO-DIGITAL TRANSLATIONS

To research the topic, students investigated structural systems that actively informed architectural tectonics (form-active structures) and explored their design possibilities with the use of parametric and/or behaviour-based computational modelling. Once the research phase was completed, students deve-

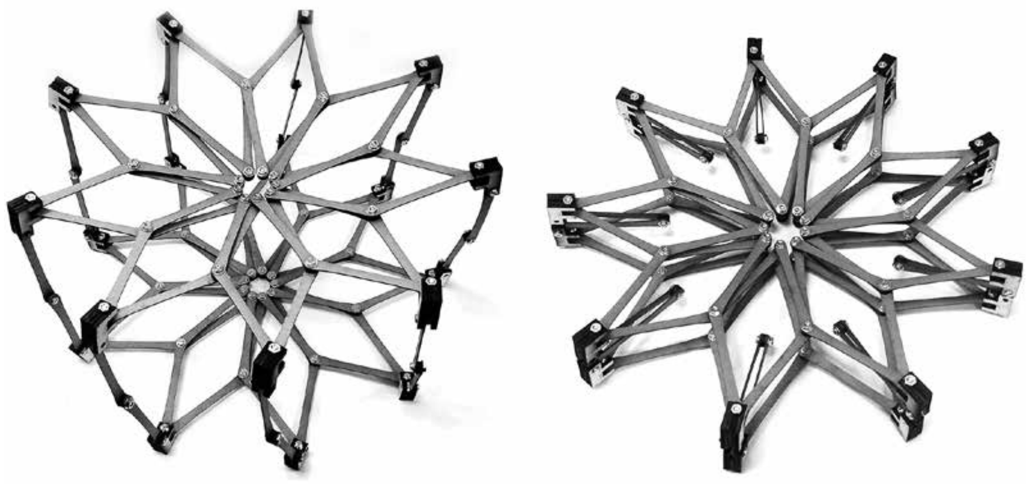


Figure 1
Deployable structural framework, conceptual model.

loped a number of physical mock-ups of the final designs to compare their behaviour with computer simulations they developed earlier for the same design.

This allowed students to reflect on the materiality of digitally designed architecture, to understand the opportunities and limitations various design tools provide, and to visualize structural behaviour in more intuitive and direct ways that available with digital tools alone. The following examples illustrate the process and discoveries students made.

Adaptive Forms

A number of projects looked at scissor-like mechanisms to develop shading and spatially adaptable systems. The project in Figure 1 investigated a deployable assembly that can be a temporary structure or an adaptive space.

Initially, students researched various relevant precedents that dealt with temporary, portable, and deployable structures. This research gave students insight into different kinetic systems, assemblies, and material applications. Students were particularly interested in the ability for the design form to be contracted into a relatively small volume and to have a low total weight. Immediately, these prerequisites started to point to the solutions of using light metal framing with a possible fabric enclosure.

In the second stage, students developed a number of conceptual studies that allowed them to apply researched systems into new spatial configurations and test their appropriateness. After developing a number of designs, both physically and digitally, students focused on the solution that followed the logic of the Hoberman Sphere. Similarly to Huberman's design, the student structure was capable of folding down to a fraction of its fully deployed size. It also used a version of a scissor mechanism. Instead of a sphere-like configuration, students experimented with a cylindrical form with the ability to expand both vertically and horizontally by increasing the cylinder radius.

After completing the chipboard model and interacting with it, students realized that the proposed structure did not have the desired rigidity and durability. Components had difficulty supporting themselves, resulting in sizable deflections. When expanding and contracting the structure, individual components were subject to twisting in the joints, resulting in kinetic friction and deformations. While this is rather obvious observation with a model made of chipboard, students also noticed

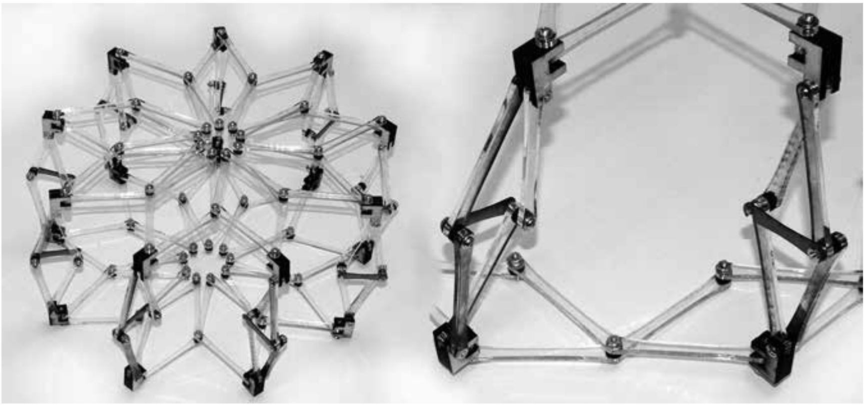


Figure 2
Deployable structural framework, conceptual model.

possible issues with the actuation of the kinetic assembly. While displacing only some, not all joints, at the same time, the softness of structural components was causing the entire system to deform, putting additional stress on connections and causing material fatigue. This was important feedback for students, since it suggested that the scaled-up structure, even when made with higher-grade material, may still have similar rigidity and stability issues.

The subsequent study model introduced more rigid material (acrylic glass), sized up the cross-section of individual components, and doubled vertical structural members. The locking mechanism was added to further stabilize the structure by introducing triangulation in the vertical supports (Figure 2).

The second project started as purely two-dimensional shading system and evolved to incorporate three-dimensional composition (Figure 3). Students similarly started by analysing various expandable designs that used scissor-like mechanisms. Their focus was on using scissors both as a structural element and as an adaptable enclosure/ shading. By testing various scissor joint geometries, they looked at possible shapes and the resulting planar tiling to provide a variety of expressions of a façade shading system.

The physical and digital explorations revealed a number of intricacies, both technical and geometrical, that were not immediately evident at the beginning of the project. What seemed like a straightforward design quickly became a complex project, particularly when multiple instances of a scissor mechanism were interconnected into larger assemblies (Figure 4). The attachment details became

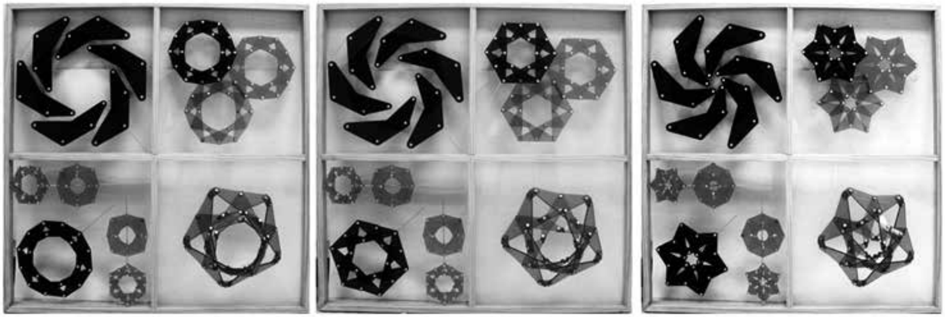


Figure 3
Façade screen mock-ups.

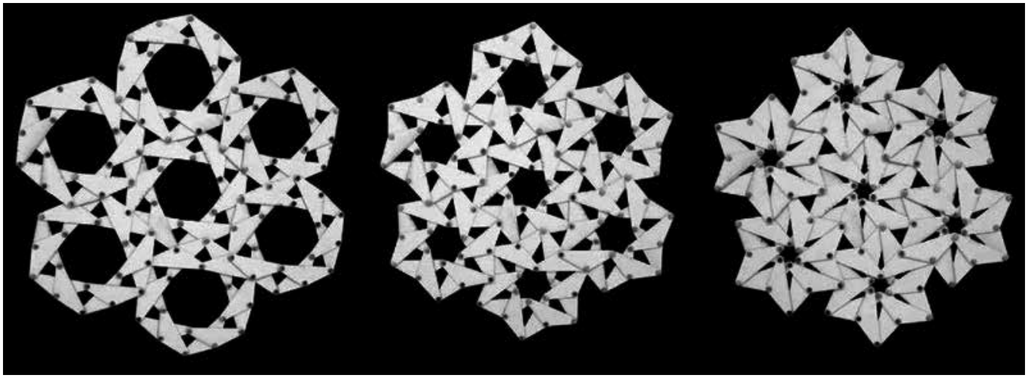


Figure 4
Aggregation of individual assembly components.

more involved, with diverse rotating and sliding motions occurring within the component connection. The connection had to account for competing movements between various sub-elements. One of the studies employed a three-dimensional version of the scissors mechanism to form a dome-like structure (Figure 5). To accommodate the three-dimensional rotation of scissor plates, students developed wedge-like adapters to control the curvature of the resultant form. Unlike other groups working on kinetic designs, this team relied heavily on physical models to complement their digital simulations. Students felt that the tactile qualities of physical models gave them valuable feedback about the levels of friction within joints and material resistance. Particularly in the situations when digital models were getting easily over-constrained and locking themselves in a fixed position, physical prototypes, due to their relative imprecision and material flexibility, gave a better indication of the overall assembly behaviour. They were also more informative because they provided a tactile feedback that helped to advance design. While laser-cut mock-ups allowed for a high level of precision, the initial prototypes were developed in the more forgiving medium of chipboard, as compared to later prototypes made of acrylic glass. This helped to track kinetic movements, particularly registering material fatigue and failures for further design refinements.

While physical and tactile feedback was important to the team, there were also limitations involved in deferring exclusively to physical mock-ups. It was often difficult to distinguish between minuscule kinetic transformation and fabrication toleranc-

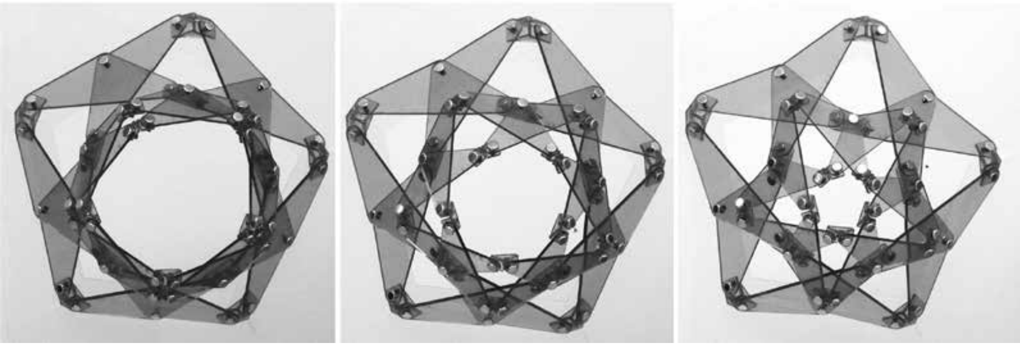
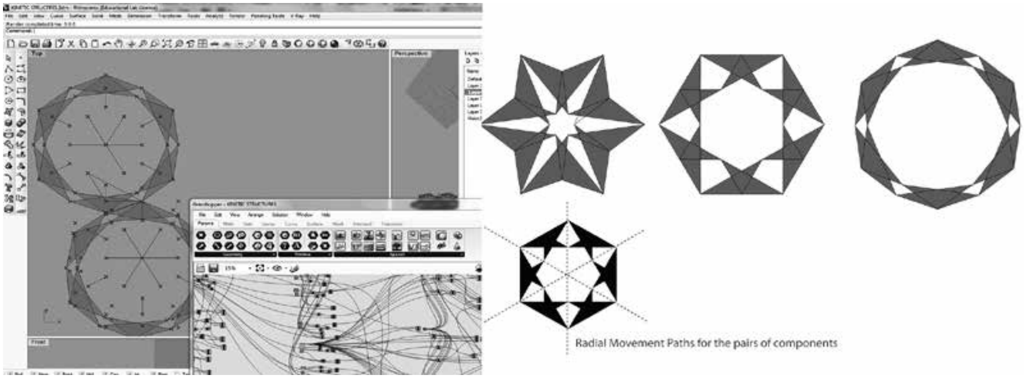


Figure 5
Applying scissors mechanism to a dome-like structure.

Figure 6
Testing parametrically geometric relationships between various components.



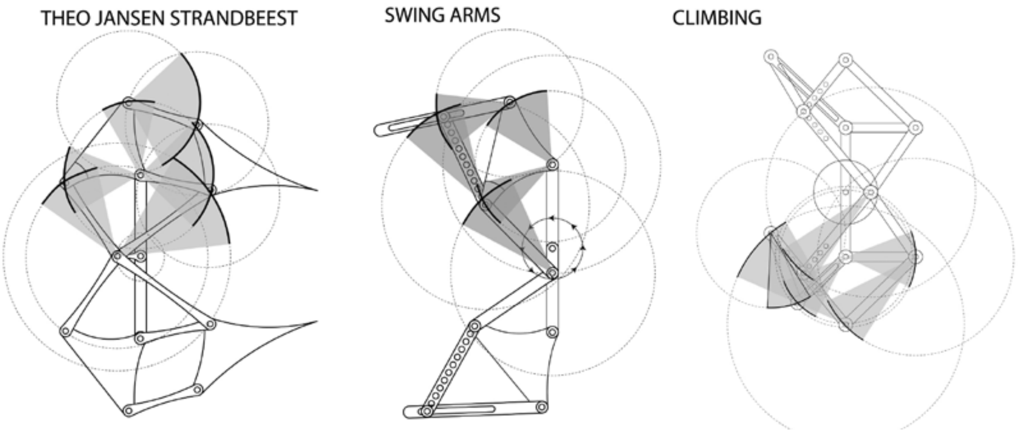
es as well as material's ability to hide stress through deformations (strain). Whereas material deformations may seem a desirable quality, these deformations may ultimately lead to material fatigue and assembly failure. To address these concerns, the design team used parametric digital models to validate their findings and fine-tune the final set of physical mock-ups. These parametric models allowed for effective tracking of numeric values and maintaining geometrical relationships between various components (Figure 6).

Once students established a general understanding of kinetic system behaviours, they became significantly more efficient in developing variations to parametric models. They were able to implement complex assemblies in more informed and intuitive ways.

Kinetic Movements

Inspired by Theo Jansen's kinetic sculptures, students investigated parametrically defined adaptive structures that mimics skeletal systems. They started with the exact replica, both physical and digital, of Jansen's Strandbeest kinetic mechanism. Then, with parametric models, students investigated how specific component dimensions and radii impact the kinetic behaviour of the entire system (Figure 7). Parametric definitions allowed for fluid changes to a

Figure 7
A study of the kinetic behaviour of the entire assembly. Original Jansen's design (left), and student design explorations (centre and right).



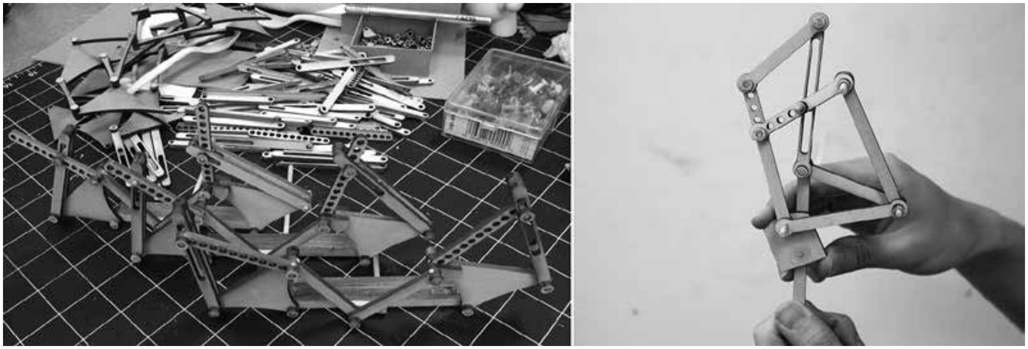


Figure 8
A kit with multiple parts worked effectively as an analog parametric study.

digital model and for immediate feedback on its kinetic behaviour. This helped to understand the role individual elements played within the entire assembly and the types of motions these elements were capable to produce.

While these parametric studies became effective tools in understanding how Jansen's kinetic sculptures worked, it became difficult to extrapolate these findings into new meaningful movements. To overcome this issue, students started with changing element proportions, folding ratios, and adding additional components (Figure 8). These speculative explorations led students to propose and develop an adaptable vertically climbing mechanism that used core principles of Jansen's models with changes to the types of constraints and possible motions.

Kinetic designs such as Jansen's sculptures that mimic walking structures, or Hoberman's expanding dome, require close and detailed understanding of kinetic mechanisms developed over time with multiple prototype reiterations. To shortcut the discovery process, students started with an already resolved design and investigated ways the logic for this particular mechanism can be extended to other forms of movement. While a physical working prototype was an ultimate goal for the project (Figure 9), it was easier to experiment with variations of the base mechanism using digital modelling.

However, conventional three-dimensional modelling software was not effective for this type of prototyping. The design team turned to parametric software, such as Revit (parametric BIM) and Grasshopper (graphical algorithm editor for Rhino), that was capable of dealing with constraints and passing these constraints between various assembly components. In addition to these two software approaches—parametric and prescriptive—the team briefly looked into VFX packages such as 3DMax and

Figure 9
Kinetic movements, final assembly.

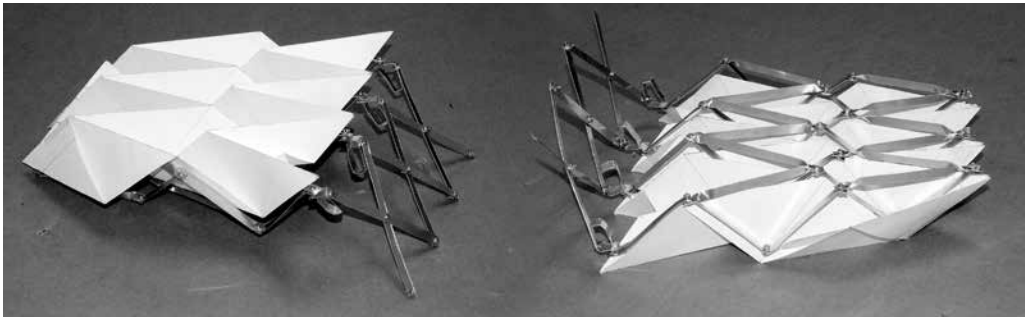


Figure 10
Rigid origami as an adaptive envelope.

Maya with inverse kinematics (IK) capabilities. While IK provided ready-made functionalities that could be applied to walking structures, the inability to directly "hack" into the algorithms behind IK functions became a significant deterrent in using them as exploration tools. Dealing with actual parameters—angle values and component dimensions—allowed students to get more direct confirmation of their initial design propositions and develop a stronger intuitive feel for the entire mechanism.

CONTINUOUS ENCLOSURES

With adaptive designs, the issue of the continuous weather tight exterior enclosure resistant to material fatigue is a major challenge. When elements move or stretch, they wear off connection seals and may cause material failures. To address these issues, students looked at form-active designs, particularly those that deploy tensile (fabric), pneumatic and foldable strategies in conjunction with kinetic assemblies.

One of the approaches looked into rigid origami as continuous yet spatially reconfigurable forms that do not rely on material deformations (Figure 10). While hinged joints provide opportunities for material fatigue, the rigid plates are durable, with all the performance qualities of traditional wall systems, including thermal and structural. Since rigid origami solutions carry a particular design signature, the underlying structural framework would naturally follow the same geometry, both from performance and aesthetic considerations. To some extent this can be seen as the limitation of the system, not only from the visual but also from the occupancy viewpoint, since the origami-generated forms are hard to reconcile with horizontal surfaces such as floors, both because of these forms' flatness and their changing height. However, they can still be effectively employed in other enclosure surfaces.

LEARNING FROM PHYSICALITY

In discussed cases, students worked with additional constraints defined by a number of component and connection types to simplify manufacturing and assembly. These became important design boundaries, focusing students on pursuing optimal solutions and driving questions of component assembly and functionality. While in some cases students did not produce an actual one-to-one mock-up, the scaled-down models became effective in setting the stage for understanding the overall kinetic system behaviour and speculating on further development of design by giving students direct feedback. The haptic feedback included not only the component movements but, more importantly, the levels of material resistance to deformations, joint frictions, and material fatigue. Additionally, physical mock-ups became a lesson in understanding issues of manufacturing precision and design and construction tolerances. These mock-ups allowed students to feel the behaviour of the material and the entire assembly in addition to visually understanding its movements.

Furthermore, the discrete numericals used in defining computational models do not help to understand the need for and the role of design tolerances. This is particularly evident in the kinetic and adaptive structures, where the movements of individual components can compound the amount of displacement and rely on material elastic deformations. The ideal computational models, BIM or not, should be able to consider these factors, and use them as design constraints and validators. Preferably, these models would provide easily understood, intuitive, and perhaps even tactile feedback that could not only evaluate but also stimulate design.

With today's generation of designers, who routinely have a better grasp of digital than of physical tools, the requirement to manually construct designs is probably even more important than in the past. Since the architectural profession ultimately deals with physically constructed buildings, there is a need for designers to understand the translation process of their ideas from the digital to the physical.

There seems to be a perception among many students that once a design is modelled in a three-dimensional virtual environment, it is fully resolved. While this may be true from the geometrical point of view, as compared to traditional two-dimensional representation of buildings where different drawings did not have to be reconciled spatially, it is not true in other aspects of design.

The present computational tools solve some of these issues but still leave many of them unresolved. Specifically, material properties, physical behaviour, and contractibility continue to remain unaccounted for in most software packages. While the approach discussed above points to ways of addressing the issues of material properties and physical behaviour, physical mock-ups prove to be an effective learning environment. By constructing kinetic and adaptive designs, students experience the intricacies of mechanical assemblies and material limitations.

The geometric precision taken for granted with software packages becomes a major issue when manually constructing kinetic designs. Centre of gravity and points of rotation are important factors in the effective operation of kinetic assemblies. The process of building and rebuilding mock-ups, discovering imprecision in produced work, facilitates the discussion on types of loads (concentric versus eccentric) and moments associated with them. Students experience first-hand the need for design tolerances and the ways they can be incorporated in their designs. Overall, students moved away from idealized computer-based reasoning toward more holistic thinking about a building as a probabilistic structure—a result of compounding imperfections and tolerances. Also, the use of advanced digital modelling tools such as BIM helped shift the design focus from the model itself toward broader and interdependent modelling of an assembly or a building (Smith and Tardiff, 2009).

SOFTWARE LIMITATIONS

Many of the physical-to-digital and digital-to-physical translations discussed above were partial and punctuated. This is particularly evident with foldable structures that utilize rigid origami. Origami designs are not easily to conceptualize and extrapolate. While there are plenty of examples of various origami designs, they tend to be difficult to extract and modify as sources for new designs (Stavric and Wiltsche, 2013). Their design requires a significant level of involvement and experience. Also, there is a limited number of software applications that can be used to explore origami design, particularly in interactive and kinetic ways. Furthermore, many of the software packages are stand-alone applications that do not port models into other applications.

For those projects, the physical modelling approach was more effective than its digital counterpart. However, the physical models did not stimulate tectonic explorations and versioning in the same ways as other projects that were realized with computational tools.

While many of the examples discussed here show only structural elements of the larger assembly, the question of how kinetic structures can be combined with an adaptive façade or building skin system is critical. For this reason, a number of students looked into form-active systems such as tensile, pneumatic, and foldable structures to see how they can be combined with kinetic assemblies to provide both adaptability and continuity of the enclosure. Consequently, a number of student groups adopted a form-active approach towards a façade or a building envelope to work with kinetic structural systems, while other students focused exclusively on the form-active design for both structure and building envelope.

DISCUSSION

Adoption of digital tools in design serves as an opportunity to redefine existing teaching and practice paradigms. This position is held by a number of practitioners, researchers, and educators who advocate the necessity of the design process change as a consequence of new computational tools, particularly BIM software (Mayne et al., 2006; Clayton et al., 2010). Individual authors propose various design frameworks. Some of the approaches focus on component-based design thinking, where an overall building is depicted as a combination of construction details (Wallick, and Zaretsky, 2009). Others advocate the role of BIM software in capitalizing on a tacit knowledge associated with any creating-making work (Clayton et al., 2010). This study aligns itself with the latter approach by emphasizing digital-to-physical translations and using materiality as a feedback mechanism to inform digital tools.

While tacit knowledge is generally acknowledged as critical aspect of the design process (AIA,1969), it is also evident that the formation of tacit knowledge (Polanyi, 1983) is associated with experiential learning and learning-by-doing. While the process of learning-by-doing can be informed by both digital and physical making, there is a particular benefit from bridging both modes of creativity. Since the end goal of the design process in architecture is a building or a structure, the ability to understand the connection between the digital design process and its physical actualization is crucial.

With the emerging robotic applications in architecture, the ability of BIM software to increasingly reflect the reality of the physical world and actual construction assemblies becomes critical. Material intelligence (MI) that is largely missing from computer applications, including BIM, sets unnecessary limits to the digital design processes. A file-to-fabrication approach works effectively when the file creator has an explicit, or at least a tacit, understanding of the materiality of the final design medium (Perez, 2010). In addition to materiality, the physics-based behaviour functionalities would allow for greater relevance and integration of digital tools in the making of architecture (Zarzycki, 2009; 2011). The methodology discussed in this paper provides opportunities for addressing material knowledge learning and the increased convergence between digital tools and building construction.

The digital-physical design dialogue is intricate and bidirectional, involving simulations, performance analyses, and component optimization. By connecting digital prototyping with physical mock-ups, material becomes an important variable—another consideration in the otherwise parametrically driven design process. Material acts as yet another feedback loop that informs design and provides a set of constraints to guide designers (Cabrinha, 2008).

Future work will focus on material translations (Decker, 2012) from physical to digital environments and closer interaction between digital and physical modes of thinking. Specifically, I am interested in simulations of material properties and physics-based behaviour to develop seamless digital-to-physical translations.

FINAL CONSIDERATIONS

The examples discussed in this paper provide a starting point for outlining the software functionalities that are missing from digital tools and digitally enabled design processes. The ultimate aspiration is that BIM, or computational models in general, assume the role of the virtualized final constructionally real designs, with the only difference between digital BIM models (mock-ups) and physical models being that computational models are actualized before a physical structure are built. While this goal is ambitious, it is also necessary in order to bring digital design process to the level where it can be deployed universally and holistically, independent of the designers' location and individual capabilities.

The present limitations lie both in computational software that does not address a number of critical design considerations, such as materiality and physically based behaviour, and also in the interface designers use to interact with virtual models. Perhaps the latter is more challenging, since it would require incorporating more sensory and intuitive inputs and breaking away from two-dimensional displays. Ultimately this would require shifting the computational interface from a mostly visual to amore dimensional feedback system that would address multiple-sense inputs.

Purely geometrically driven digital models miss many design opportunities. What may seem a failure of resolving constraints within parametric BIM systems with physical models can be a close enough (good enough) solution that material elasticity and tolerance allow to function, giving a designer an important clue of being in the proximity of a solution. The binary quality of computational feedback may often be misleading, particularly in the boundary conditions when investigated designs lie immediately outside the zone of computationally correct solutions. A more forgiving and probabilistic approach associated with physical models and materials may often be more informative and effective as a design tool. Feeling material behaviour provides a broader design feedback than simple "works" or "does not work" (over-constrained) statements.

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Understanding and Managing the Constructive Characteristics of Vernacular Architecture

Two raw earth dwellings

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Abstract. *In this paper a methodology will be presented to investigate and document the constructive characteristics of two raw earth houses: artifacts that belong to the vernacular architecture. The comprehension, analysis and documentation of these architectures presents several problems mainly linked to the impossibility of using a predefined method, because the difficulties relating to each artifact and its characteristics, to particular geographic, cultural and social situations, are unique. To understand and document the constructive features it was decided to realize a three-dimensional digital reconstruction of the two artifacts, using 3D modeling software. Subsequently several graphic works have been elaborated (technological breakdown, sheets with detailed information about the materials, used constructive techniques, etc), useful in managing a recovery or maintenance project.*
Keywords. *Vernacular architecture; raw earth dwelling; 3D modeling; digital reconstruction; knowledge management.*

VALUES OF VERNACULAR ARCHITECTURE

In this paper a methodology will be presented to investigate and document the constructive characteristics of two raw earth houses, artifacts that belong to the vernacular architecture. The use of the adjective "vernacular" next to the word architecture was first used by Rudofsky (1987) and it means an artifact that has been built by common people (hence not by professional figures such as architects) to satisfy particular needs, such as to shelter or inhabit. This spontaneous architecture is widely diffused worldwide: it constitutes about the 90% of the world's buildings (Oliver, 2003) and it possesses a remarkable value because it is an expression of the environmental and cultural characteristics of a place and of the way of life of its population (May and Reid, 2010). It defines the identity of a site, its cultural diversity, hence it should be preserved for present and future generations. Furthermore, it represents a precious deposit of meanings, materials and constructive systems that can be used as a source of inspiration during the design and build of more sustainable buildings.

Unjustifiably the interest in the application of the digital technologies in this architectural sector is not well diffused, although these constructions have inspired (and still inspire) many (even famous) architects (such as Renzo Piano for the Jean-marie Tjibaou Cultural Centre in Noumea, New Caledonia, but there are other famous examples, such as Frank Lloyd Wright or Le Corbusier). They have particular spatial and material qualities, which make them more fascinating than many anonymous modern and contemporary buildings designed by professionals.

ISSUES STUDYING VERNACULAR ARCHITECTURE

The artifacts belonging to vernacular architecture can be broadly classified into various categories: domestic, agricultural, industrial, religious, etc.
Each of these categories can be further divided into subcategories: for instance, domestic architectures can be further divided according to the place (city, countryside, etc.) and to the dimension, but other differences can be taken into consideration (Brunskill, 1988). The technical-constructive solutions and the materials used in vernacular architectures strongly depend on the geographic features of the place where they are located: materials can be found on site and in surrounding areas, but climatic conditions, together with social and cultural aspects also play an important role. It is often possible to have very different constructive techniques within the same geographic area. The aesthetic, morphological and technical-constructive variety of vernacular houses worldwide is impressive (Oliver, 2003).

The comprehension, analysis and documentation of these architectures present several problems mainly linked to the impossibility of using a predefined method, because the difficulties related to each artifact and its characteristics, to particular geographic, cultural and social situations, are unique. This uniqueness characterizes the use of unique terms that indicate specific technical elements of a particular construction, and for this reason it is necessary to deepen the knowledge of the object that has to be studied through documents and the communication with local people.

OBJECTIVE OF THE RESEARCH

The main objective of the research is to define and test a methodology to analyze and document the constructive characteristics of two raw earth houses. Raw earth is one of the most used building materials. The concept of constructive characteristics indicates the constructive system of an artifact, referring to the number and type of technical elements and the materials that comprise it, to which requirements it corresponds and how they are connected/assembled.

The analysis and documentation of the constructive characteristics of vernacular architecture is interesting for various aspects:

- to produce a knowledge (understanding of the artifacts) and documentation aimed to the definition of recovery, maintenance and renovation projects;
- to learn from the past sustainable constructive solutions that can be updated and used to create a healthier and more human built environment. These new solutions could be exported in other contexts having the same characteristics, and in this case this should be considered as "technological transfer".

As time passed by, most of the know-how related to these constructions got lost, including the technical-constructive knowledge and the capacity of organizing a recovery site. It is not always possible to understand some technical-constructive solutions by only consulting the existing documents or observing the real artifacts. The digital technologies, and in particular the application of 3D digital modeling packages, allow us to investigate and compute many characteristics of buildings that have been built spontaneously, without a predefined design. Hence we can find out details such as the number and position of technical elements, the quantity of materials used and other technical/constructive characteristics.

THE CASE STUDIES

For this research two dwellings located in two countries have been chosen (both belonging to

Figure 1
(Left) - Picture of the dwelling in Loreto, abandoned and in ruin (Source: picture provided by Prof. M.C. Forlani); (right) - Picture of the inner courtyard of the house in raw earth (Source: picture provided by the working group of Africa '70 project).

the Mediterranean area). In this way the similarities and the differences between the two constructive systems have been compared. The two artifacts belong to the same category, domestic building and have a similar size. Both case studies analyzed by the author belong to wider researches coordinated by Prof. M.C. Forlani (G.d'Annunzio University, Chieti-Pescara, Italy).

General description

- **Loreto (Abruzzo, Italy):** The house (Figure 1 left) is located near Loreto, a small village in the countryside of the Abruzzo region, in central Italy. In this region there is a long tradition of raw earth buildings and to date a number of over 800 artifacts have been surveyed (Forlani, 2011). The typology of the artifact is a tower type, like many other buildings in raw earth in the region, and it is located in a rural area with no other buildings nearby. The constructive technique is the cob (made by clay, sand, straw, water and earth), but other dwellings in the region are also made by rammed earth.
- **Figuig (Marocco):** The analyzed building (Figure 1 right) is located in the city of Figuig in the eastern area of Marocco, at the border with Algeria. The city, built around an oasis, consists of seven ksour which are typical fortified villages in north Africa. In a ksar (that is a single village) there are collective structures such as barns, shops, religious buildings and private homes. The houses have courts and they are all juxtaposed to form a compact urban tissue which facilitates defensive actions. The main constructive material for all the structures is adobe (the composition is similar to the cob, the difference is that the dough is shaped into bricks (using frames) and dried in the sun; in some cases it is possible also to find cut stone.

Issues to be faced

- **Loreto (Abruzzo, Italy):** The artifact is abandoned and in ruin. Due to different climatic conditions (mainly snowfall and rainfall), the artifact is badly damaged, the roof and the floor are partially collapsed and also the perimetral walls present fissures. Moreover, the dwelling is surrounded by vegetation, in particular blackberry bushes. With this situation it was dangerous to enter inside the building or to move around easily and take more information and pictures.
- **Figuig (Marocco):** In this second case the main difficulty was due to the impossibility of visiting the place personally, together with the necessity of analyzing a non-standard building system.

METHODOLOGY

Both situations required the use of digital technologies of 3D modeling. To study and carry out the two digital reconstructions and create a series of graphic works to document the constructive peculiarities of the two raw earth houses, it has been defined a similar methodological process that can be synthesized in four main phases:

- Collection of documents;
- Analysis of the whole available documentation;
- Digital reconstruction (interpretation, modeling and organization of the elements);
- Representation and organization of the information in worksheets.

The digital reconstruction phase

In order to understand and document the constructive features of an artifact, the most appropriate choice is the realization of a 3D digital model. The traditional two-dimensional drawings (plans, elevations and sections) do not allow an analysis, a representation and a proper communication of the constructive features. These graphic works are an ineffective theoretical description of the information concerning the technical elements and their relations in the three-dimensional space: this information can instead be provided by a 3D model. Moreover, the two-dimensional drawings have some inconsistencies which document and communicate the information in an unclear and wrong way, even because of difficulties caused by the irregularity of the technical elements that come from a non industrial production (hence not standardized). The two-dimensional drawings are not adequate for studying irregular morphological-constructive artifacts, because in these situations they appear to be excessively approximate.

The expression digital reconstruction means a process that foresees the action of building again as an existing artifact (or an artifact that no longer exists), in a virtual environment. This process possesses an autonomous value, independent from further analysis, because the same reconstruction process contributes to deepen and broaden the knowledge of the artifact. During a process of digital reconstruction there are many choices to be taken.

During his Ph.D. research, the author examined and underlined the importance of some aspects that have to be considered when undertaking a three-dimensional digital reconstruction process, namely: abstraction, geometry and organization of the model. The model that results from the digital reconstruction is, like any other model, a simplified description of a system [1].

In the analysis of the artifacts and in the digital reconstruction as reference a classification scheme, namely the Italian UNI norms (UNI Norm 8289/2, 1981 has been used. In particular, these norms have been a useful support to the understanding and classification of a complex system made up of a hierarchical structure of the technical elements. The norms have been properly readjusted to describe a non standard building and only the classes of technological units available in the artifact have been selected.

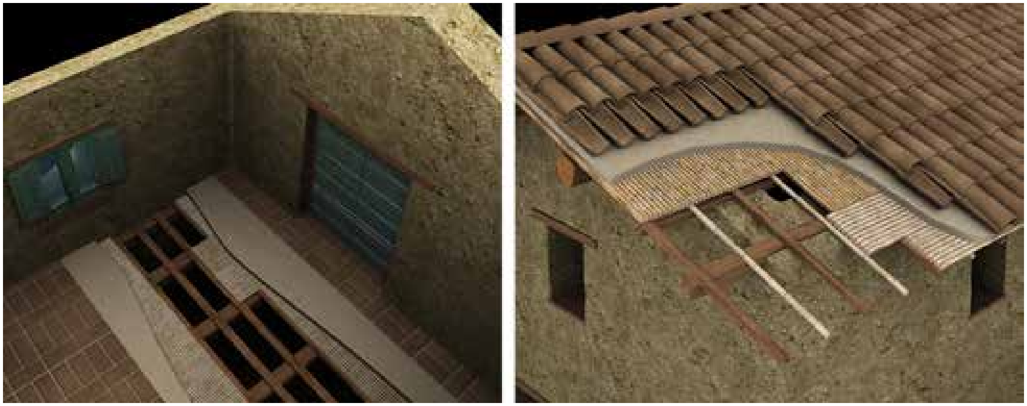
The case study of Loreto

The information gathered about the dwelling in Loreto are the results of some previous researches, including a photographic documentation, a two-dimensional survey in Autocad, that includes plans, elevations and sections, and worksheets with the information about technical elements (floors and walls) belonging to other raw earth dwellings of the region.

The dwelling, made of just two rooms is located on a slight slope and it is partially recessed in the ground. This characteristic affects the access to the two rooms positioned on opposite walls and at a different layout level. The room on the ground floor was used as stable/warehouse, while the room on the first floor represents the real dwelling and it was used as kitchen and bedroom.

Even in this case, like in the digital reconstruction of the Figuig dwelling, the two-dimensional drawings (properly cleaned of irrelevant information and reorganized into layers) have been really important within 3D Studio Max. The first elements

Figure 2
(Left) - the constructive system of the floor (internal view of the room on the first floor); (right) - rendered view of the constructive system of the pitch roof.



to be modeled have been the four perimeter walls, built with the technique of the cob and tapered upward. The wall surfaces, because of the taper effect, are therefore inclined both inside and outside of the artifact. Three sides of the building are mutually orthogonal, while one side has a different inclination. The influence of this detail in the technical-constructive solutions clearly emerged during the study of the floor. The floor consists of a double frame of wooden beams: a main structure (beams of square section, 15 cm x 15 cm) and a secondary one perpendicular to the first (rafters of rectangular section, 8 cm x 3 cm). The beams are partially embedded in the masonry load-bearing and probably the rafters at both ends are embedded in the walls. The space between the beams is always constant, the only exception is the resulting surface between the last rafter parallel with the rest of the secondary and not the one built into the wall at right angles to the others. On the secondary structural grid is positioned a lattice of rods which constitutes the basis of a layer of clay (about 8 -10 cm thick) on which it is resting in the flooring tile brick (called "pianelle") of rectangular shape (Figure 2 left). The structure in raw earth did not allow large openings in the walls, which is why the number and size of windows are limited. On the first floor there are three windows, two on the ground floor. The openings have frames (lintels, jambs and sills) and fixtures (including the shutters) in wood. The sills on the outside of the openings over the windows are in brick tiles ("pianelle"). The pitch roof has a bearing structure with a double wooden grid. On the second structural grid, similarly to the floor, is positioned a lattice of rods that constitute the base of a mantle in earth-straw. The external layer is made up by clay roof tiles (Figure 2 right).

In order to provide some quantitative data on the number of elements for this house two examples have been chosen: the tiles, about 310 for the pavement of the ground floor and about 366 for the flooring of the first floor (where have also been used on the input threshold of the house) and roof tiles, about 1007. Obviously, this numerical and quantitative information is indicative because there is the awareness of being in the presence of elements which do not result from manufacturing, and that can also significantly vary in size from one another. For both projects a set of textures to communicate the materiality of the technical elements has been created.

The case study of Figuig

The collected basic information include a photographic documentation, technical data on slabs and roofs, a two-dimensional survey in Autocad, which includes plans, elevations, and a section with the description of the materials. The artifact of study is

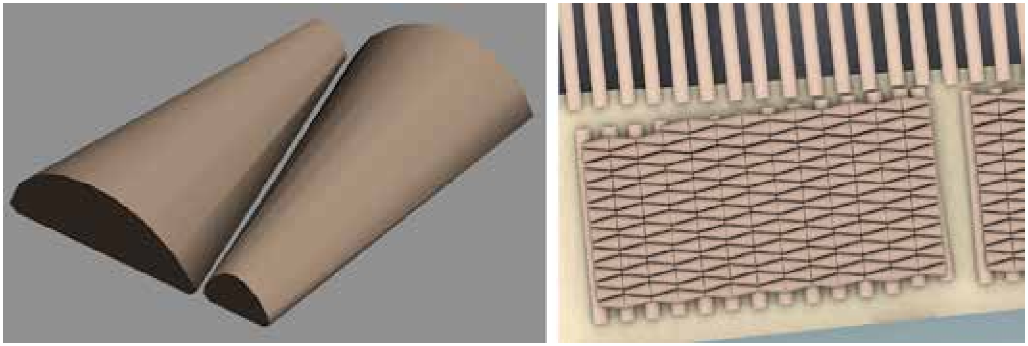


Figure 3
(left)- rendered image of two karnef; (right) - closure of the slab in karnef on palm wood beams.

inserted within a compact urban settlement, characterized by buildings with courtyard. The walls border with other houses - therefore they are common walls - or with paths, some of which are covered. The building has a courtyard and three levels, two of which are practicable: the ground floor, the first floor and the roof/terrace.

The floor plans in Autocad have been cleaned by dimensions, crosshatchings and other non essential details, and imported in the 3D modeling software, 3D Studio Max. The use of a 3D modeler, instead of CAD software used for precision drawing like AutoCad, is the proper tool to model and manage a non standard artifact composed by a high number of objects on screen. Almost all the basic elements have been created through extrusions, and the most relevant exception is made of *karnef*, semi-triangular wooden elements that constitute the base of the palm trees.

This digital reconstruction investigated and documented the constructive aspects of the artifact, therefore for this reason special attention was paid to the analysis of the grid of the slabs. The grid is made of palm wood beams and the lower closure of the roof in contact with the beams is in *karnef*, which are elements that also play a structural function. The span between two beams where the *karnef* are placed is of about 34 cm; the *karnef* have an average size of 30 cm and they are between 3 and 5 cm high. The length of the palm wood beams varies between a minimum of 140 cm and a maximum of 270 cm. This wide margin of difference comes both from the variable dimensions of the environments, and from the irregular thickness of the wall (Figure 3).

In order to cover all the spatial units in a constructively rational way and to understand the technical problems that could arise from this constructive technique, the beams and the *karnef* have been manually positioned, as if they were actually building the construction in a traditional way (Figure 4). Each beam has been rotated, spaced from the previous and adjusted in its length to correctly adapt itself to the spaces that have to be covered and to adjust the upper layer of the *karnef.* The position of the *karnef* on the same row is alternated and each row of *karnef* is mirrored with respect to the previous row.

The digital model also allows to calculate/ assume the quantity of some technical elements necessary to build intermediate floors between the ground floor and the first floor (both floors of the court and those of the individual rooms): about 286 palm timbers on which are placed about 4209 *karnef* (1951 for the ceiling of the court and 2258 for indoors).

REPRESENTATION AND ORGANIZATION OF THE INFORMATION IN WORKSHEETS

In both digital reconstructions all the technical elements have been grouped and divided per layer, according to categories of homogeneity, belonging to a floor plan or a specific field. The first prepared

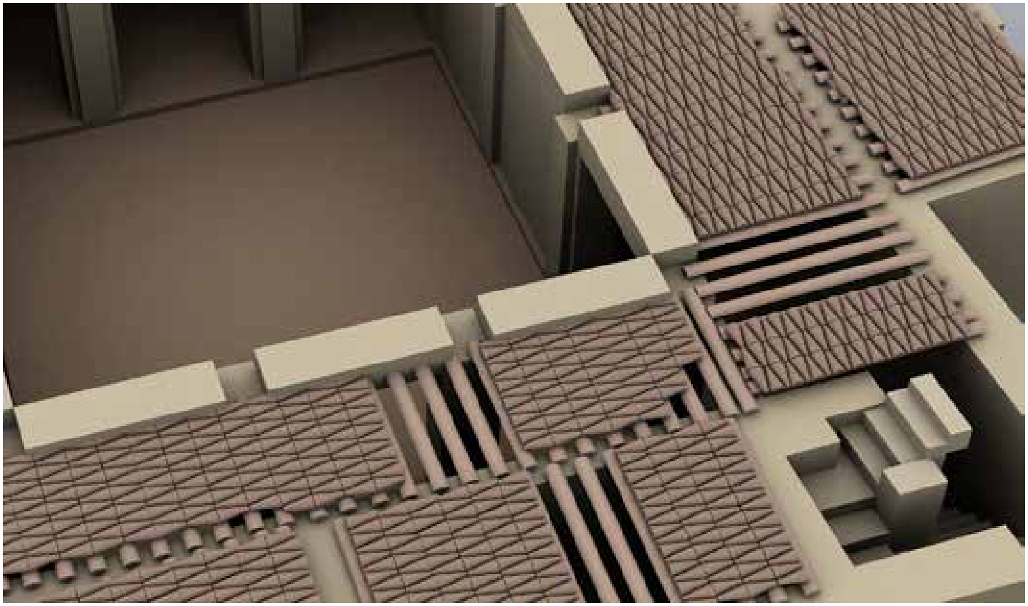


Figure 4
Rendered image of the grid and closure of the roof of first level.

graphic work is the representation of the technological breakdown: an axonometric exploded view of different levels of the artifact, from the ground floor to the slab of the roof. The levels are related to re-adapted categories, from the UNI Norm 8290 of the technological breakdown. This scheme clearly communicates the affiliation of each layer to one or more of these categories, and therefore its function. Other graphic works are made of analysis worksheets of the main technical elements. For Figuig the masonry (Figure 5 left) and the slab (Figure 5 right) have been documented. The worksheets have detailed information about the materials, the constructive techniques, the constructive phases and the performances of materials and technical elements, referred to specific classes of requirements. The methods used to document the different construction phases, called evolutionary characteristics, have been described and analyzed by the author in other publications (Di Mascio, 2012a; 2012b). The obtained information has been reorganized taking into account the possibilities of realizing a database to combine all the information gathered and elaborated during various inspections and researches.

DISCUSSIONS OF THE RESULTS AND FINAL REMARKS

The realization of the digital models of the two dwellings in raw earth located in Marocco and Italy have allowed an in-depth study of their constructive systems and to hypothesize technical solutions adopted in some critical points which could be difficult to analyze and document in other ways. The produced information is useful to undertake technically efficient interventions on the built environment, without compromising the local architectural and constructive culture. As for other researches undertaken by the author in the field of digital media and cultural heritage (Di Mascio, 2009), the three-dimensional model was recreated in 3D Studio Max, because the digital reconstruction has required tools able to guarantee a better control of the frequent modifications and to quickly visualize various hypothesis on the adopted constructive solutions.

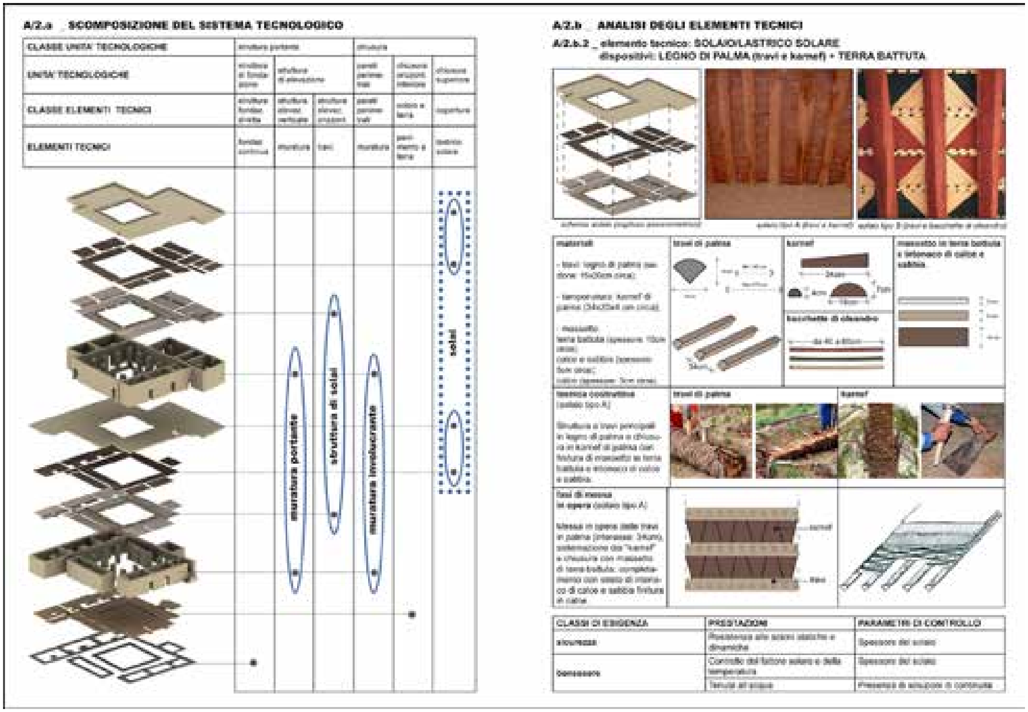


Figure 5
(Left) - Technological breakdown of the raw earth dwelling of Figuig, with the indication of the elements according to the classification scheme proposed by the UNI Norms;(Right) - Analysis card of the technical elements: Slab.

In these cases a certain level of creative interpretation is also necessary, because there are still many information gaps to fill. This methodology is particularly suitable in the study and analysis of non-standard artifacts pertaining to vernacular architectures as for example the Turchinio's trabocco (Di Mascio, 2009). During the digital reconstruction work a major technical problem due to the high number of 3D elements used for the roof tiles, the *karnef* and the tiles of the floor has also been tackled.

The two case studies, although they have material and technical-constructive characteristics in common, clearly present evident differences, mainly due to matters linked to their geographic localization, but also to different life styles: different roofing systems, the presence or absence of windows, different organization of the spaces / environments, different materials used, etc..

Most of the literature available on vernacular architecture consists of descriptive texts, pictures and drawings (sketches and two-dimensional reliefs). The use of 3D digital reconstructions is another step forward in observation, analysis, documentation and management of these artifacts, because it allows the investigator to assess and monitor additional parameters, such as spatial and quantitative, that methods and tools so far available did not allow to analyze with the same precision and effectiveness. Obviously the study and testing of these digital technologies must be accompanied by a continuous processing and verification of theoretical and methodological apparatus. The introduction of new methods and tools always leads to a critical re-evaluation of what has been done so far and the opening of new avenues of study and research. In the study of vernacular architecture (as in many other fields of knowledge) it will be increasingly important to become aware of the importance of multidisciplinary approaches in order to bring the studies in this area to a higher level of detail and quality. Effective collaboration between specialists from different disciplines (architects, engineers, historians, anthropologists, archeologists, geographers, and many others) will largely depend on the ability of everyone to communicate to others in a clear and effective way information related to their area of expertise. Communicating the technical-constructive information only through two-dimensional drawings and texts could limit the comprehension and hence the capacity of other specialists to contribute to the research, influencing negatively the final result. The methods and analyzing instruments in the field of vernacular architecture are still too compartmentalized in the single disciplines and this could be limiting (Oliver, 2006).

CONCLUSIONS

Within this research methods and tools to improve the comprehension and documentation of two raw earth houses have been investigated, elaborated and proposed. During the digital reconstruction phase it has been possible to interpret, suppose and document technical-constructive solution, that, in the best situations, could be understood only after several inspections, which could not be performed in both cases.

The reconstruction of a three-dimensional digital model can improve and expand the knowledge of vernacular architecture in order to improve the understanding, documentation, management, and conservation and simultaneously stimulate and evaluate the use of technical solutions and new constructions. Digital technologies and new theories and methodologies resulting from them are not intended to replace traditional methods and tools, but to complement and help to achieve new levels of accuracy and in-depth information and reflections. Textual descriptions and two-dimensional graphic works alone are not able to trigger some technical-constructive problems that come to light only during the digital reconstruction. A continuous testing of additional case studies will be very useful to improve and expand the theoretical and methodological approach, and of course the use of various digital tools.

This approach can be used in an efficient way to rebuild and analyze many vernacular architectures in a digital environment; this refers in particular to huts, villages on stilts, buildings in stone, raw earth, and many other pertaining to different cultural and geographical environments worldwide.

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3D Digitization in Architecture Curriculum

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Abstract. *In this paper we describe an experience undertaken in the Faculty of Architecture of Technical University of Lisbon, concerning the introduction of a 3D Digitization course in the frame of the PhD doctorate program in Architecture and in the frame of the Master's programs in Architecture, Urbanism and Design.*
We start by describing the theoretical and instrumental frameworks proposed. Then we describe and discuss a set of two exercises developed during one semester, giving examples of the work produced by the students. Finally we end with some considerations to be taken into account in future editions of the course.
Keywords. *3D digitization; architectural recording; laser scanning; digital photogrammetry; teaching and learning.*

INTRODUCTION

In the book Digital Design Media, Mitchell and McCullough (1995) describe a design studio fully integrating traditional and digital media. Basically the Building is at the centre and several paths are displayed between the building and its possible forms of representation, being Digital Models one of those forms. According to the presented and well known scheme, the shortest path between the building and the Digital Model is through electronic surveying. This electronic surveying encompasses what can be designated as 3D Digitization.

There are multiple techniques of 3D Digitization, passive and active (Lillesand et al., 2004), range based and image based (Remondino, 2006), using different kinds of light, etc.

This paper describes an experience of implementing a 3D Digitization course in Architecture curriculum.

The goals of this experience were to make architecture students familiar with 3D digitization techniques and tools, to develop their awareness for the possibility of doing themselves the work, to use freeware and open source software as much as possible in all the workflow from data processing to the final models scaling and orientation, and to propose a theoretical framework for the teaching and learning process of this subject among architecture students.

3D Digitization was offered as an optional course at our University. It could be attended by Architecture, Urbanism and Design master students during their fourth or fifth year of their studies, and by PhD Architecture students during their first year.

This paper is structured in six sections: a) a short history and related work, b) the theoretical framework, c) the instrumental framework, d) the practical exercises proposed, e) Results of the exercises and discussion, and f) conclusions and further work.

A SHORT HISTORY AND RELATED RESEARCH

Traditionally the survey of the built environment was driven to the production of 2D deliverables. This was particularly truth before digital technologies become a common place. The techniques used were the traditional manual and topographic survey, analogic photography and analogic photogrammetry, that relies in the human faculty of perceiving in objects 3D, from pairs of images (anaglyphs), with the aid of some specific instrumental apparatus.

Photogrammetry was then a very expensive and specialized technique, and very time consuming, since all the work was done manually. One of the obvious fields of application was the survey of monuments surfaces.

During the 80ies and 90ies, digital technologies become into broader use. Photogrammetry meets another stage, the analytic, meaning that a computer was used to translate into numerical format the analog inputs of the operator. In this way, although the restitution process was still manual, it became possible to store 3D data in digital format. This was one initial form of 3D digitization as something more direct between the object and its 3D digital model representation. By the same time the topographic survey with electronic distance measurements devices was also in use, but it could only provide a much more discrete digitization that was generally used to set ground control for the photogrammetric survey or for the traditional manual survey (Mikhail et al., 2001).

In the beginning of the nineties optical triangulation scanners time-of-flight laser scanners were introduced. And at the beginning of this century a new kind of scanners, phase-based, much faster, become also into use. Dense point clouds changed the way 3D digitization was done.

Simultaneously, advanced image processing techniques were developed that enabled the use of 2D images to produce 3D dense point cloud models in an almost unattended way.

With the increasing power of computation capabilities, and the sophistication of software, it become more feasible, easier, accessible and cheaper to deal with bigger amounts of data, and in general, to access to 3D digitization. This was also the result of some kind of merging between the fields of photogrammetry and computer graphics.

In the academic field, in the context of architecture, the insertion of digital technologies opened a Pandora's Box and an endless, and sometimes meaningless, discussion about the harms and benefits of the digital (Mitchell and McCullough, 1995).

Some authors (Duarte, 2007; Duarte et al., 2010) have presented successful experiences about the insertion of digital technologies in the architectural curricula and even mention 3D scanning as part of that insertion (Pupo et al., 2008) in the context of digital fabrication.

On the other hand there is a tradition that follows from the survey field, often linked to architectural heritage documentation or archaeology, that nowadays, fully use 3D digitization techniques, such as terrestrial laser scanning (TLS) or digital photogrammetry (DP). In this context it is common to see courses of Architectural Photogrammetry often supported by Photogrammetry or Survey Labs [1] [2].

We understand 3D digitization as a fusion of these two views, the tradition of survey and photogrammetry and the field of Computer graphics (Remondino, 2006). As being part of a school where we have a diversified range of academic offers, going from Fashion Design and Design to Architecture and Urbanism, we think that 3D digitization techniques can be used with benefit in all these scales, not just in a mere instrumental way, but adding new reflexive possibilities to the praxis. That was the motto for the creation of the 3D Digitization course.

THE THEORETICAL FRAMEWORK

The theoretical framework focuses on acquaintance with the basic knowledge of concepts by the students that allow them to operate in a proper way in an architectural context, mostly from a user standpoint. This is done in a three step approach going from the principles level, to the guidance level and finally to the specification level (Wu and Di, 2009). These three levels work as a metaphor both for the teaching and learning and for the practical framing of the work.

First we start by discussing the 3D digitization techniques and methods in the broader context of recording techniques (Boehler and Heinz, 1999), and these as a tool for the understanding of the built structures (Letellier, 2007). At this level is also important to notice what kind of 3D models can be produced and to understand in what contexts different models are used (Chader, 2008). This is in the principles level.

Then we selected a subset of the 3D digitization techniques as a subject to address in more detail. Namely we selected terrestrial laser scanning (TLS), as an active range based technique, and photogrammetry as a passive image based technique, in particular with the structure-from-motion/multi-view-stereo – SFM/MVS (Snavely, 2008; Furukawa and Ponce, 2009) approach. We discussed the typical workflows and its usual steps and concerns, such as planning data acquisition, data processing, model refinement and model orientation. With respect to model orientation we gave an overview of matrix representation of the transformations of scale, rotation and translation and how to estimate the transformation parameters from homologous sets of data points. This is in the guidance level.

Finally, the specification level corresponded to the statement of terms that students had to follow to accomplish two practical exercises.

THE INSTRUMENTAL FRAMEWORK

The instrumental framework comprises a hardware part and a software part. Both parts are interconnected and influence each other. So, it was necessary to make sure that all students could accomplish their exercises even if some kind of limitation arises.

For the SFM/MVS approach we recommended, but didn't limit to, three operative alternatives: a) My3DScanner [3], b) Photosynth [4] + Photosynth toolkit 11 [5], and c) Visual SFM [6]. The first option implies that all the processing of images is done online, so it suited to students that have severe hardware limitations. The second option allows doing some steps of the processing online whilst other steps are done locally, so it is suited to medium hardware capabilities. The third option implies that all the processing is done locally what obliges to have better hardware capabilities but also allows a more effective control of the process.

Both for TLS and SFM/MVS point clouds processing, it was recommended MeshLab [7] and CloudCompare [8] as well as Notepad++ [9] and Libre Office Spreadsheet [10] for some manual manipulation of matrices.

For the estimation of transformation parameters, namely for scaling, rotation and translation of the point cloud and mesh models, we recommended JAG3D software [11].

This is a collection of freeware software, some open source, totally available in Internet, what means that all the steps of the workflow, from the point clouds processing from acquisition to the final textured mesh models, can be done at no cost.

This means a bigger democratization of the access to digital recording media. The exception to this rule is the parsing of terrestrial laser scanning point clouds from the proprietary format of the scanner supplier to a more common format such as PTX or PLY, which was done with proprietary software. Since we own a FARO Focus 3D laser scanner, we used Faro Scene to solve for this step.

THE PRACTICAL EXERCISES PROPOSED

Two practical exercises were proposed to the students.

In the first exercise, the students choose an architectural or sculptural detail from which they should be able to produce a textured mesh model, without holes. This was supposed to be done solely from photographic imagery. To scale and orient the produced model, two homologous data sets of points are to be used. One is obtained from the point clouds and the other should be the result of independent measurements done directly in the selected object or scene. In addition to the models, in the end of the exercise, the students should submit a report describing and justifying their options during the work.

In the second exercise, a common set of point

Figure 1
Left: illustration of a reference frame. Center: Cameras relative orientation. Right: Dense point cloud.

clouds, from a terrestrial laser scanning survey of a building, was given to all students. They were asked to follow a described procedure to align the point clouds, to dissipate accumulated errors, and to produce a final merged and sub-sampled point cloud model. This contributed to a broader investigation on the development of an expeditious method for dissipating what we designated as a closure error that arises from the alignment of a closed ring of point clouds.

RESULTS AND DISCUSSION

In this section we describe the workflow that was adopted to do the two aforementioned exercises. While describing the steps of the exercise we will also describe the competences that were supposed to be acquired by the students as well as the difficulties that were felt.

First exercise - 3D digitization small or medium scale object using image based techniques

The objective of the first exercise was to produce a textured mesh model of a small or medium scale object in an architectural context using automatic image based techniques following the structure-from-motion (SFM) principle. First of all it was declared that this kind of techniques have severe limitations in their use to record poor textured surfaces or very reflexive ones, since they rely on the texture of images to recover 3D information. This fact should be understood as constraint about the kind of object that should be chosen; rich texture objects were more adequate.

The statement of the exercise consisted of 10 steps.

- Defining a reference frame in the object. In the simpler form it could be set out as a couple of measurements with a measuring tape in a flat rectangular surface from which one could retrieve the coordinates of at least four control points (CP) as it can be seen in Figure 1 (left and center). Although control points should be widely spread about the object, for the exercise it was allowed to consider them more locally, whilst noting that the first procedure is better since it diminishes the scaling and orientation error.
- Image acquisition. This step involves the understanding of the SFM principle. Images need to be taken with small base distances, what means that the camera view point in space must always be changing and large amount of images of images with a high level of redundancy is to be taken. It is noticed here that there is no need to use high resolution images. In fact it is better to use more images with less resolution and adopt a hierarchical strategy while taking the pictures. This means that several rings of images at different camera/object distances should be considered. This implies another constraint to have in mind when choosing the object to digitize; the surroundings of the object have to be accessible.
- Image processing is the step where colored dense point clouds are generated. Although this is done automatically we believe that the correct approach is to provide to students

some insight into the phases of this step so this doesn't look like a black box. To understand what happens during this process, even if it is at a superficial level, helps the students to acquire the needed vocabulary to discuss with experts, in in the future specialized services are required, and helps bridging the gap with the service providers. This phase includes the following sequence controlled by a set of parameters that determine the quality of the results: a) SIFT, b) image matching, c) cameras relative orientation, and subsequent sparse point cloud generation (Figure 1 right), and d) dense point cloud reconstruction.

- If the outcome of the previous step is more than one point cloud independently placed, then it is necessary to proceed to the relative orientation. Usually, according to the characteristics of the objects and procedures, it is expected that the generated point clouds share the same coordinate frame, that is, the relative orientation comes as a result of the cameras relative orientation. Relative orientation of point clouds will be discussed in more detail in the next exercise.
- Following from the previous step, if one has multiple point clouds, they should be merged to produce a single model. This is important if we want to produce a final "water proof" model that can be used, for example, in digital fabrication. Before merging, spurious data should be removed from the point clouds.
- External orientation is the operation that recovers scale and orientation of the model in the reference coordinate frame. In fact the control points generated in the first step suffice to solve for the seven parameters of the Helmert transformation, that are one scale factor, three rotations and three translations. This is the step where the students with less Math's background feel more uncomfortable. So it is needed to do some extra exercises to explain how homologous data sets can be used to estimate transformation parameters, and to explain the least squares criterion.
- After the final point cloud is oriented, it follows a decimation operation that results with the purpose to have an even spatial resolution.
- Then a mesh model is created.
- If there are any holes in the mesh they should be filled.
- And finally the color of the points is transferred to the mesh to produce more appealing and realistic models, as it can be seen in Figure 2.

One of the outcomes to achieve with this exercise was to understand that, for many purposes in the architecture framework, one can obtain reliable 3D data without the use of very expensive hardware and without having to hire specialized services. At the same time, by taking into account the restraints that were mentioned, students are capable to understand the potential and limitations of the SFM approach.

Second exercise - relative orientation of terrestrial point

The objective of the second exercise was to orient a given set of 16 terrestrial laser scanning (TLS) point clouds forming a closed loop around an existing building. The point clouds were acquired with a FARO Focus 3D. They were parsed and decimated to 1cm spatial resolution a delivered to the students in the PLY format. This allowed to have smaller files and made the process more feasible. The basic concerns with this exercise were to compare the quality of TLS and SFM/MVS point clouds, to provide a way to evaluate the quality of the orientation process through the analysis of a closure error that arises when one tries to close the loop, and to provide a method for the acceptance and correction of that error by distributing its translation component proportionally to the distances between the origins of the frames of the point clouds.

The statement of the exercise consisted of 5 steps.

- First the point clouds have to be cleaned. Data that presumably didn't remain stationary between scans had to be removed. Otherwise the

Figure 2
Some of the models that resulted from the first exercise.

registration (orientation) errors would increase. This task was divided by all the students.

- Then, the set of cleaned point clouds was oriented by a specific order and criteria; each point cloud should only be registered with the previous one and a particular point cloud was set as the reference frame, what means that its position is given by an identity matrix. This way, the final results could be compared. After each registration step, after optimization with the iterative closest point (ICP) algorithm, the student should visually verify if the quality of the registration. This can be easily done by inspecting the point clouds with at least two mobile plans with different orientations and analyzing the section that they produce in the model.
- When closing the loop, that is, when orienting the last point cloud (that is simultaneously the first) with the previous one (the last of the set) its matrix position represents the accumulated error. We refer to this as the closure error as in topography (Casaca et al., 2000).

Figure 3
One of the point cloud models that resulted from the second exercise.

- If the closure error is found to be under the acceptable tolerance, then we can consider that no gross errors occurred and we can distribute the error through the poses (matrices) of the point clouds as mentioned above.
- Finally the point clouds were merged and decimated to produce the final model.

In Figure 3 we present an example that resulted from the second exercise.

With this exercise it was possible to verify the need to be careful when dealing with multiple point clouds because if the work is not well controlled, it is easy to accumulate large errors or even to make blunders. Students are then told that there are complementary methods, such as topography, to control the overall quality of the process. But it is also noticed that for medium scale objects, such as the church surveyed, it is possible to use TLS as a standalone method. As with SFM/MVS it was also underlined that there are surfaces that aren't good candidates for laser scanning recording. Among those there are glassy surfaces or low reflectance surfaces.

CONCLUSIONS AND FURTHER WORK

The practical results obtained showed that, with a minimum of theoretical framing, satisfactory results can be obtained by agents that are not usually from the field of specialized surveying, and almost with no costs. We notice that, at the PhD level some of the students were architects that didn't even knew about the existence of some of the methods and tools discussed.

It was also interesting to notice that that fact didn't prevent them from accomplishing all the exercises with high quality results. This means a shift in the paradigm for architectural recording and means bridging a gap between fields of knowledge that traditionally were separated. At the end, it was achieved the idea that new possibilities arise by adding these methods and tools to the architect toolbox. It was possible to understand that the techniques presented can be used alone or together or complemented with other techniques, such as topography or manual survey.

We also noticed that, in some cases, the lack of mathematical background of some students caused some difficulties when dealing with matrix notation and when operating with geometrical transformations via matrices. The issue was easily overcome with complementary materials and exercises where those difficulties were addressed. This is unavoidable since there are some degrees that don't offer mathematics on their curricula and the course doesn't have any prerequisite.

The contents of this course focused in the point cloud processing towards the production of scaled textured mesh models. It is necessary to understand that, usually, this is not an end in itself, but rather a starting point for further modeling. The discussion with the students at the end of the semester pointed out they felt to have acquired a very important tools for the future, but they also noted that it would be interesting to give a further step in the application of the produced models.

As a consequence, in future editions of this course, broader concerns will be considered, namely, practical uses of these models and how to use them as positional, geometric and radiometric constraints for the production of other kinds of 3D models such as Nurbs models or CAD/BIM models.

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Performing the Past and the Present for the Knowledge of the Future

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Abstract. *The aim of this paper is to discuss the role three-dimensional models play in addressing performance issues in virtual reconstructions of the heritage buildings. Heritage visualisation is considered here as a process of representing knowledge about space, time, behaviour, light, and other elements that constitute cultural environments. The author aims to analyse the process of digital reconstruction of heritage buildings and the impact of the decisions taken during its development on the final performance. Based on the examples drawn from practice, various stages of development are discussed, confronted with the principles of London Charter.*
Keywords. *Virtual reconstructions; cultural heritage; 3D modelling; London Charter.*

BACKGROUND

Information technologies support a number of domains, including - among the others - virtual modelling of built heritage. One of the earliest examples of such projects was a reconstruction of ancient buildings in Bath, which was done as early as 1983 (Dave, 2005). Another example might be Winchester cathedral which was modelled in 1984-1986. A decade later the Urban Simulation Team from the University College in Los Angeles was commisioned a real-time visual simulation model of the Forum of Trajan, the largest of the Imperial Fora in the Forum Romanum for the exhibition at the Getty Center. The project aimed at exploring the historical, cultural, and technological information contained within ancient works of art as well as examining new ideas in archaeology, conservation, scholarship, education, and digital technology (Jepson and Friedman, 1998).

For many years, digital reconstructions have been presented and discussed at the eCAADe conferences. The author also contributed to this subject (Kepczynska-Walczak, 2003). However, the use of 3D modelling in the virtual reconstructing of heritage buildings is no longer a subject of research itself. It rather opens new fields of research and application. First, it is necessary to indicate approaches to considering a heritage building reconstruction as a data container. For example Boeykens and Neuckermans (2009) studied the possibility to improve and increase information by adding supplementary metadata to the 3D model through “metadata enrichment”. According to the authors “this structured information can, in turn, facilitate the retrieval and recovery of such models, when searching or browsing for design information through online architectural repositories”. Another interesting project was the use of BIM deployed in the historical reconstruction of the Vinohrady synagogue in Prague (Boeykens et al., 2012). It is worth mentioning here the book devoted to the former Viennese synagogues that were destroyed and disappeared from the city space. Rebuilt virtually, accompanied with the historical photographs recreate and perform the past in the context of the present day city (Martens and Peter, 2011).

Other contributions of particular interest include ornament modelling and deployment of rapid prototyping technology in making physical models (Breen and Stellingwerff, 2008) and augmented reality (AR) allowing better understanding of original appearance of a heritage interior and instant comparison with an extant state (Tonn et al., 2009).

Concurrently, at the beginning of 21st century researchers started to express their interest in the computation and the performance in architecture (Kolarevic, 2003). The subject is complex due to the multiplicity of associated meanings, including sustainable, technical, social and semantic issues. The performative approach was also implemented in the case of built heritage objects (Albayrak and Tunçer, 2011). Authors stressed the importance of "the shift in the orientation of architectural theory and practice from what the building is to what it does. Therefore, it defines the architectural object, not by how it appears, but rather by its capability of affecting, transforming and doing; in other words, by how it performs". Their research suggested that this method might be useful in the heritage conservation - in this case in transforming fortifications of Amsterdam, listed as the UNESCO World Heritage.

CREDIBILITY OF VIRTUAL RECONSTRUCTIONS

In the light of the above, it is clear that contemporary digital technology offers a vast arsenal of techniques of modelling, representation and analysis. Objects of any chosen time period can be reconstructed and placed inside their original context. Especially in cases where the building is not existing, is demolished or largely renovated or altered, the reconstructed model can be used to provide insight into the evolution of the building or the site.

In this context the interpretation issues seem extremely important, especially when the reconstruction of not existing object is being considered. In such case it is only a supposed, hypothetical image of a building based on the archival documents. However, the resources are often either incomplete or represent only architectural drawings, while implementation records are usually not available. This means that it is often impossible to confront the above-mentioned archival documents with an executed object due to the lack of photographic images or other reasons. The problem of trustworthiness emerged already with the first pioneering reconstruction drawings made in the 18th century by Giambatista Piranesi, who filled them with a number of imaginary elements. The foundations of scientific approach to the subject were laid in the mid 19th century by Austin Henry Layard and Luigi Canina, who paid a particular attention to the evidence and veracity of performed reconstructions (Dave, 2005).

The subject of reliability was recently discussed also in the context of 3D modelling of heritage buildings. A good example of problems emerging in this field might be a question of light analysed by Hauck (2009) in the Hagia Sophia in Istanbul. In this case, the researcher dealt with the problems of reflection of materials. Although a number of various ready-made rendering software were deployed, the results remained unsatisfactory, especially when compared with the existing object. The solution was the use of an open source program, which allowed to write appropriate scripts to expand capabilities of the software. What is more, the modelled building was visualised with the use of 'sky models', depending on the location, date and time. The 'sky models' were provided by the International Commission on Illumination - also known as the CIE after its French title, the Commission Internationale de l'Eclairage - an organisation devoted to worldwide cooperation and exchange of information on all matters relating to the science and art of light and lighting, colour and vision, photobiology and image technology.

An issue of great importance was also raised by Earl (2011) who dealt with the problem of insufficient data and, in consequence, tried to answer a question how to visualise the hypothesis proposed by researchers - in this case by archaeologists. In other words, computer based visualisation tools have the capacity to create convincing reconstructions of historical structures that appear to be authentic and complete. The challenge is how to make the process of reasoning drawn from relatively limited evidence, more self-evident in the model and also make known the alternative options that were possible but less probable.

Therefore, virtual reconstructions of heritage buildings might be considered as a process of representing knowledge about space, time, behaviour, light, and other elements that constitute cultural environments. What is more, data credibility is of particular importance in the development of the society of knowledge.

LONDON CHARTER

Taking into account the current state of research already presented and the issues of the virtual reconstruction reliability, it is of crucial importance to present the London Charter for the Computer-based Visualisation of Cultural Heritage [1], which was conceived in 2006 to ensure the methodological strictness of visualisation as a means of researching and communicating cultural heritage. The Charter was officially approved by several national and international bodies, including the Italian Ministry of Culture, which adopted it as an official guideline.

In the Chapter preamble it is stated that the document "aims to enhance the rigour with which computer-based visualisation methods and outcomes are used and evaluated in heritage contexts, thereby promoting understanding and recognition of such methods and outcomes". What is more, authors indicate a number of earlier documents and initiatives (including AHDS Guides to Good Practice for CAD and Virtual Reality, Virtual Archaeology Special Interest Group and Cultural Virtual Reality Organisation), which stressed necessity for scholarly reliability of virtual visualisation methods, as well as the care for the choice of an appropriate form of presentation of research results, reflecting the current state of historical knowledge. The central issue is clear distinction between facts confirmed by sources and hypotheses and differentiation degree of probability of arguments.

What is interesting, similar assumptions were made some 80 years ago, when the Athens Charter for the Restoration of Historic Monuments was adopted in 1931 during the First International Congress of Architects and Technicians of Historic Monuments. For example, it was stressed that in case of a heritage building reconstruction new materials used for this purpose should in all cases be recognisable. Such an approach to the heritage reconstruction was developed in the Venice Charter in 1964: "the process of restoration is a highly specialized operation. Its aim is to preserve and reveal the aesthetic and historic value of the monument and is based on respect for original material and authentic documents. It must stop at the point where conjecture begins, and in this case moreover any extra work which is indispensable must be distinct from the architectural composition and must bear a contemporary stamp" [2].

Therefore, the London Charter is of great value and importance, since the availability of powerful hardware and software allows to perform delusively realistic reconstructions. What is more, at present nearly everything can be straightforwardly published on-line and, in consequence, easily available to unlimited number of the Internet users. This might be regarded as a great advantage but, on the other hand, there is a risk that laymen lacking analytical capacity may consider those visualisations as representing the truth - according to notion "seeing is believing". Such situation in case of virtual modelling may cause erroneous interpretations of a history. This issue was further developed by some authors, who indicated that although for certain purposes visualisations can exceed text in an expressive power, their explanatory value may be poor. Therefore Denard (2012) stressed that "for a heritage visualisation to match the rigour of conventional research, its rigour must be visible. That is why, at the heart of The London Charter is the principle that heritage visualisations should accurately convey to users the status of the knowledge that

Figure 1
Virtual reconstructions of the Scheiblers chapel at the Lutheran cemetery (left), the Richters villa (top right) and the Mutual Credit Society (bottom right).

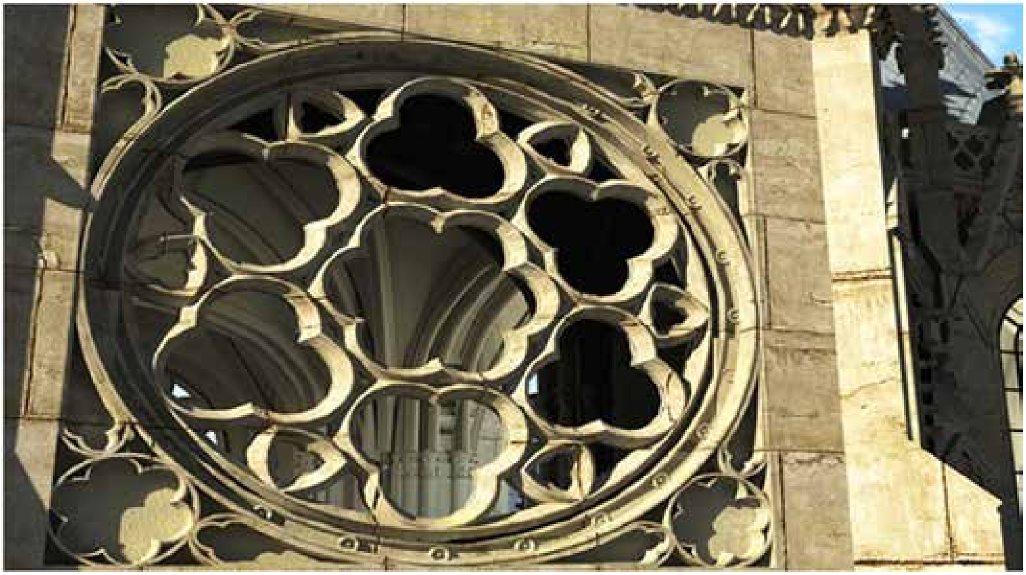
they represent, such as distinctions between evidence and hypothesis, and between different levels of probability."

CASE STUDIES ANALYSIS

The purpose of this section is an analysis of a digital imaging process of heritage buildings and the impact of decisions on the final output. The analysis is based on examples taken from the author's didactic experiences in virtual reconstruction. Parallel references to the London Charter (LC) allow better understanding of its principles and practical application.

The issues related to credibility of virtual reconstructions are based on the cases of historic buildings in Lodz, including the Richters villa, the Scheiblers funeral chapel and the Mutual Credit Society premises (Figure1). All the buildings represent various architectural types and forms from the late 19th century. The Mutual Credit Society, built in the 1870s, is an excellent example of neo-renaissance public edifice. The Scheiblers chapel is an impressive mausoleum of one of the most prominent textile manufacturers in Europe and his family. This building erected in 1888 is one of the best exemplars of 19th-century European gothic revival. While the Richters villa illustrates the living conditions in the industrialist residence at the turn of the 19th and 20th centuries.

Figure 2
The rose window of the front façade of the Scheiblers chapel.



It is necessary to stress that all the above-mentioned objects exist, so the process of digital reconstruction required a high quality realistic representation in accordance with Rule 6 of LC: "the creation and dissemination of computer-based visualisation should be planned in such a way as to ensure that maximum possible benefits are achieved for the study, understanding, interpretation, preservation and management of cultural heritage (…) The aims, methods and dissemination plans of computer-based visualisation should reflect consideration of how such work can enhance access to cultural heritage that is otherwise inaccessible due to health and safety, disability, economic, political, or environmental reasons, or because the object of the visualisation is lost, endangered, dispersed, or has been destroyed, restored or reconstructed."

Among the principal goals of analysed cases was an education, including the dissemination of Lodz cultural heritage, allowing access to these magnificent buildings which are not open to public due to their current state and use. What is more, the Scheiblers chapel has been listed by the World Monuments Fund as one of 100 most endangered sites in the world since 2006.

The inventorial measured drawings and photographic documentation were used as the initial material for digital reconstruction. The inventory was made using a hybrid method that combines a traditional analogue and digital techniques of documenting heritage buildings. The range of measurement drawings included not only the shells of buildings, but also their interiors. The high level of accuracy was obtained, which can be seen on some of details drawings. Therefore, such comprehensive data enabled to create very detailed digital models (Figure 2 and 3). Unfortunately, it was impossible to use 3D scanning due to high costs. Despite the growing knowledge on this technology among the conservators, the financial barrier makes 3D scanning in Poland not widely used in heritage documentation practice.

Pursuant to Rule 4 of LC the goal was clearly defined - to reflect the existing state: "4.4. It should be made clear to users what a computer-based visualisation seeks to represent, for example the existing

Figure 3
The lantern at the main entrance of the Richters villa.

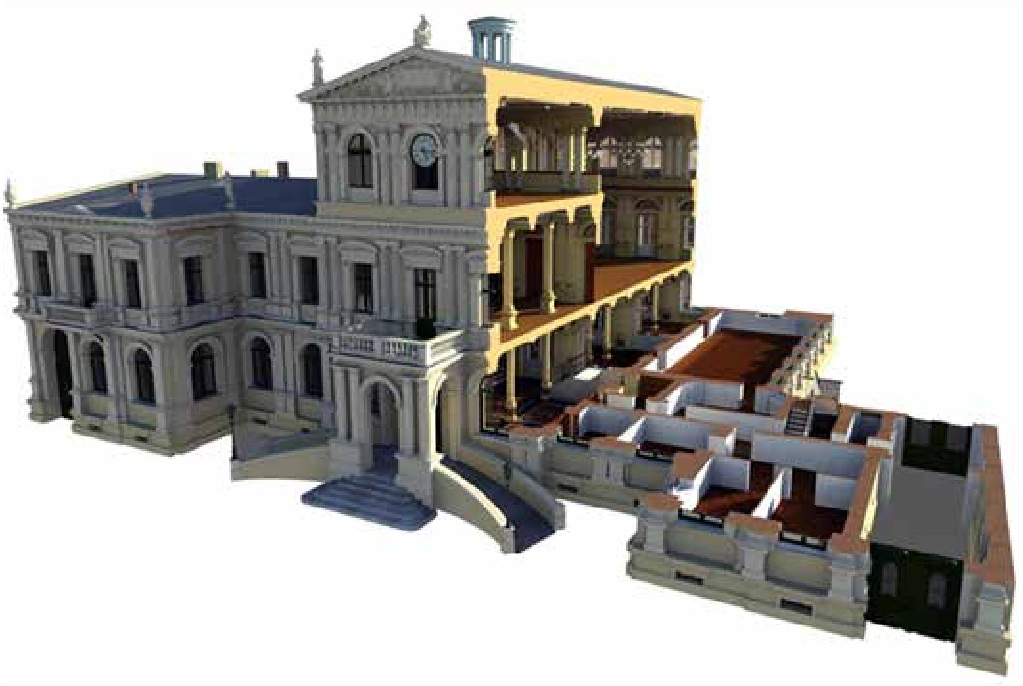
state, an evidence-based restoration or an hypothetical reconstruction of a cultural heritage object or site, and the extent and nature of any factual uncertainty".

In the context of the above the question arises whether - referring to the London Charter principles - a model and subsequent visualisation, made on the basis of the inventory, are sufficiently reliable for "study, understanding, interpretation, preservation and management of cultural heritage"? On the other hand, however, one of the principles of LC is that "the costs of implementing such a strategy should be considered in relation to the added intellectual, explanatory and/or economic value of producing outputs that demonstrate a high level of intellectual integrity".

Discussed reconstructions present high level of details - not only exteriors but also interiors were modelled carefully (Figure 4). Special regard was paid to the issues of lighting and texturing objects, including, in particular, the problem of texture mapping and performance of the same texture in different lighting conditions (Figure 5). Texturing turned out to be a very difficult task, many attempts have been done to achieve an effect similar to reality. It was impossible to use textures from photographic pictures since in different lighting conditions the same material performed different appearance. Another interesting observation was a selection of lighting - mimicking the actual lighting conditions in a virtual environment, the virtual textures changed their characteristics unlike to what could be observed in reality. What is more, a colour palette of the interior successfully reproduced in one visualisation, turned up different from the actual interior appearance in another visualisation.

It is worth to confront the observations with one of the objectives of the London Charter, which "seeks to establish principles for the use of computer-based visualisation methods and outcomes in the

Figure 4
The three-dimensional cross-section showing variety of volumes and spaces within the Mutual Credit Society building.



research and communication of cultural heritage in order to (…) ensure that computer-based visualisation processes and outcomes can be properly understood and evaluated by users".

To sum up this section, it is necessary to stress that the ability to confront the results achieved in the process of creating the virtual model with the actual state allowed the ongoing verification of the decisions and to introduce necessary adjustments. It might be argued that the situation was comfortable since modelled objects existed. Nonetheless, it was impossible to avoid the compromises because, as the experience has shown, a reliable digital representation depends not only on the input data.

SUMMARY AND CONCLUDING REMARKS

The considerations put forward in the first part of this paper relate to the reconstruction of non-existent, destroyed objects and to existing structures. The main obstacle of such tasks lies in limited source materials. On the other hand, it is relatively easy to accept the achieved results, since it is impossible to compare them with the actual building. On the contrary, when the existing object is a subject of modelling, it is perfectly possible to achieve its geometry through the measuring or scanning. However, there is much stronger pressure on reliable representation of real appearance. It is not easy if not just a general impression but the knowledge about the object is to be represented. What is more, the problems associated with modelling of existing structures make clear that reconstructions of non-existent objects may occur extremely imperfect.

Similar problems apply to other fields of art - such as sculpture. For example, replicas made in a different material, although keep shapes of originals, trigger different aesthetic experience. The topicality of the above-mentioned issues can be proved by

Figure 5
The entrance hall and the main stairs of the Mutual Credit Society edifice.

the solution adopted in the Tate Gallery on-line catalogue, in which objects could be seen in a different light exposure, allowing their better understanding, including texture and other features (Stanicka-Brzezicka, 2012).

To summarise, the author aimed to analyse the process of digital reconstruction of heritage buildings and the impact of the decisions taken during its development on the final performance.

Assuming that the imaging is treated as a visualisation of knowledge, these issues are of particular importance, since contemporary culture is based on the visual perception, in which not intellect, but the senses are activated to experience the past [figure 6.]. What is more, the image acts as the dominant form of memory. According to Szpocinski (2009) memory visualisation is a phenomenon which essence is the dominance of visual events in the processes of transmission and perception of the past.

Taking above issues into account, the author believes the paper will contribute to the discussion on performative values of virtual reconstructions in the cultural heritage domain.

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Figure 6
The pulpit and the presbytery of the Scheiblers chapel.

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Building Information Modelling

Challenges of Integrating BIM in Architectural Education

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Abstract. *This paper provides a critical overview of some of the fundamental issues regarding the adoption and integration of BIM – both as a method and as a technology – in Architectural education. It aims to establish a common ground for the rationale behind such integration and reflects on the past and present state of the cultural, intellectual, professional and technological context of Architecture. The paper will introduce the core issues to be considered in order to succeed in this challenging and transformational process. It will also introduce a framework for a gradual and progressive adoption of BIM and integrated design in the architectural curriculum.*
Keywords. *Architectural education*; *BIM and integrated design; distributed cognition; integrated design studio.*

INTRODUCTION

The emerging visions for an "Integrated Practice" in building industry, through BIM (Building Information Modelling), carry potential to fundamentally transform the way in which architectural education engages with issues of design knowledge, technology, representations and collaboration (Ambrose et al., 2008). In this article we aim to develop a framework for the integration of BIM into architectural education. We also aim to identify the core issues to be considered in order to succeed in this challenging transformational process.

In UK, the government has set out an ambitious plan to have fully collaborative BIM, with all project and asset information, documentation and data being electronic, on all public sector projects by 2016. The UK programme based on this new BIM strategy is seen as one of the most ambitious and advanced government led programs to embed the use of BIM across all centrally procured public construction projects. Through this Government-led incentive, the construction industry is getting ready to utilize BIM as a stepping stone in order to be more efficient and effective. So how do these ambitions affect architects and architectural education at large? The RIBA believes that architects have a central role to play in ensuring that the construction industry responds to the opportunities offered by BIM in both public and private sectors and has developed a new Plan of Work (launched in May 2013) as an important piece of new guidance for architects and co-professionals [1]. However, there is yet no guidance or a roadmap for architectural schools/institutions as to how they could adapt to the forthcoming challenges in the industry and to educate the future architects accordingly.

There are both complementary and contradictory views as to "if" and "how" BIM – either as a software, or as a process or in any combination – should be integrated into the academia's curriculum structure. Some of the resistance stem from a shared set of concerns which have been outlined by some of the contributors of a recently edited book by Deamer and Bernstein (2011); *1) architectural curricula is already overloaded and there is no room for any more content, 2) The inherent practice-driven approach of BIM methodology is not compatible with the explorative character of design thinking, 3) the structure of the architectural curriculum is not suitable to adopt BIM*. Other factors have also been reported as impeding the successful adoption of BIM in the design curriculum, such as; varying definitions and interpretations of BIM by different professions; issues regarding accreditation, and disproportionate emphasis on "technical skills" (Kiviniemi, 2013).

There are two major areas where BIM will have direct impact on the architectural curriculum. First is its implicit proposition as to how design and project partners should collaborate, and the second is regarding how information (geometric and non-geometric) can be modelled, embedded and shared during the entire project life cycle. However, using a BIM software doesn't automatically guarantee a superior level of collaboration, unless conditions for a successful collaboration are met which is not only through software. Similarly, the ability to virtually model both geometric and non-geometric project information doesn't immediately bring maximum efficiency unless the representations are modelled and shared properly, the information needs in the process are correctly understood, and a robust technical infrastructure and a proper business model to support this process are present. Therefore a view of BIM solely as a software would be a rather superficial and unsustainable approach. The focus should instead be on the principles that the concept of "integrated design and project delivery" was founded on in the first place, so the changes in the curriculum wouldn't become obsolete each time a new BIM technology is developed and introduced.

The paper will initially identify the rationale behind BIM integration into the Architectural curricula (both as a concept and as a technology) and some of the common misunderstandings which impede its successful adoption. It will then try to explicate some of the fundamental reasons for the resistance against BIM. A critical review of some of the existing educational approaches will be followed with the introduction of a new framework for BIM integration into the architectural education, a discussion regarding some of the pedagogical and cognitive issues, as well as the future of the profession.

DEFINING A COMMON GROUND AND RATIONALE

BIM is widely used as the acronym for 'Building Information Modelling' which is commonly defined using the Construction Project Information Committee definition as: '...digital representation of physical and functional characteristics of a facility creating a shared knowledge resource for information about it forming a reliable basis for decisions during its life cycle, from earliest conception to demolition.' [2].

Before posing the question of "how to", it's essential to revisit an important question: What is the rationale behind using BIM in the first place? Obviously, one would easily argue that the ways in which architectural education will embed BIM into its curriculum - with supporting pedagogies - must be compatible to the rationale behind it and somehow guide this transformational process. The answer to this question is explained in a most recent government documentation as 1) promote greater transparency and collaboration between suppliers and thereby reduce waste (procurement, process and material) through all levels of the supply chain 2) enable intelligent decisions about construction methodology, safer working arrangements, greater energy efficiency leading to carbon reductions and a critical focus on the whole life performance of facilities [3]. In other words, without any specific mention to any specific technology or software, the message is: *how we used to collaborate, make decisions, exchange information, use and organize our time and resources in the past in design and construction sector have been full of inefficiencies causing a lot of waste of time, money, and resources*. *And this needs to change.* This is a statement which each and every person in our sector, including architectural educators and even the biggest BIM sceptics would probably agree with. BIM, in this present time, is "a proposition" as "a possible solution" to tackle some of the major problems of our industry. And just like every proposition, it comes with its own methodology, supported by its own technical infrastructure, implemented as a "technological solution" by various software providers, albeit with variations in their focus and in the support they provide, and with certain bottlenecks.

One of the biggest misunderstandings about BIM and the changes associated with its integration into our work practices is to compare it to the shift from drafting (on tracing paper) to CAD. Firstly, the shift from tracing paper (as 2D drawings) to CAD (as 2D computer files) did not change the outputs that were issued to the industry (Kiviniemi and Fischer 2009). Consequently, it didn't have a major impact on the structure and the hierarchies in the sector, nor required new working methods. However, already the shift from level 0 BIM to level 2 BIM (domain specific, federated models) does indeed pose fundamental changes such as; *Handling and creating information rich models, new ways of working with other stakeholders, re-aligning the disciplinary roles and responsibilities, opportunities for new additional roles for Architects*. Although even the definition of level 3 BIM (fully integrated models) is at the moment somewhat vague, it will introduce new challenges in the future. These changes become great challenges that will relate to training and education of Architects that cannot be solved simply by adding new content and skills to the existing curriculum, but will also necessitate the modification and deletion of some of the existing content.

THE STATUS ANXIETY AND THE ROOTS OF RESISTANCE

The discussions surrounding the "BIM integration into Architectural education" should not be understood in isolation, but in connection with the general changes of the relationship between architectural schools and professional practice since the beginning of the 1990s. For the most part of the 20th century, Architectural education has been looking to cultural studies and literary criticism for its theoretical models, minimizing its operative and technical capacity (Allen, 2012), and thereby created a substantial divide between architectural theory and architectural practice. 1990s marked a big shift from cultural theory to building practice in the academic circles. Theory dominance began to subside as new architecture practices emerged which better suited to meet the challenges issued by globalisation. Today, globalisation, digital technology, environmental change, and increasingly market-driven education economy are already reshaping academia (Ockman and Williamson, 2012). Consequently, there have been changes in the curriculum to address a broader understanding of social, economic, technological and cultural variables in order to design buildings which perform to higher environmental and energy standards. However, still a majority of architectural schools are following the traditional educational models with less engagement with technology and with the larger community of the built-environment that make up the building industry. Having made this distinction, it's also important to note that concerns over BIM integration into the architectural curricula are not only limited to the more conventional schools of architecture. A certain level of scepticism and hesitation exists even among the most technology savvy schools, although they have since long embraced new design methods and technologies in their curriculum and research programmes.

Although there are a few innovative and successful implementations of BIM in current practice, architectural education has been slow to respond. There are two issues to understand about the existent resistance. One is associated with some of the established values embedded deeply within its professional culture. The other is due to the nature of architectural education as an institution, and the cultural and intellectual capital it entails. Professional education in Architecture doesn't only provide the necessary epistemological and cultural context for architects, but also helps define the social and professional context within which architects work and operate within the construction industry. Although there are distinct variations in the positions different schools of Architecture take, there have always been an unspoken but almost anonymously accepted cultural norms and codes as to how architects associate themselves with the rest of the construction industry and within the society at large (Stevens, 1998).

BIM is not just a new technology. If it was just another CAD, or another piece of technology, architects would have already been the first to adopt and advocate, as we have already been witnessing through the highly creative and innovative use of the recent parametric and computational "digital design software" both in practice and in various Schools of Architecture. BIM has an implicit proposition as to how the sector should/could be realigned, restructured and work together. In other words, it will have wider social and professional implications within the sector, which makes its potential future users more hesitant. And this is probably at the core of one of the least pronounced reasons for resistance against BIM, especially by the educators in architecture, that is; by entering into an unchartered (BIM) territory architects can become a mere player, one of "the others", instead of "the creator, the innovator". BIM is not a fixed or a finished concept or methodology, and technology is continually being updated and developed to meet the industry needs, giving way to the emergence of new concepts and insights on a continuous basis. Another justified reason for the existing anxiety is about how to integrate something that is not yet theoretically nor practically complete into an "educational system" which is historically based on established theoretical and discursive models? There are various concerns that naturally follow this discussion, such as:

- How will the changes affect our accreditation status?
- How will the existing staff adapt to the new skills and knowledge required by this fast moving and industry-led approach?
- Can creative artistic expression co-exist with collaborative practice?
- Can we retain and protect our professional values in a new-found collaborative and democratic pluralism?

A GENERAL REVIEW OF CURRENT EDUCATIONAL EFFORTS OF BIM INTEGRATION

A recent study suggest that universities are lagging behind the AEC industry in terms of adopting BIM technologies and improved collaborative working practices, and that universities are not currently meeting the needs of industry in terms of collaborative building design and BIM education (Macdonald and Mills, 2011). A majority of developments in UK relate to the emergence of new master courses in BIM and Integrated Design as well as CPD courses addressing to different disciplinary groups. This makes sense as they are fast track options and provide concentrated content. They usually address to a multi-disciplinary audience and therefore entail rather generic content. They do not always address the individual disciplinary challenges and often aim to provide "an introduction" to the subject. CPDs and software-vendor led trainings usually provide more discipline specific teaching, and can range from more theoretical to more technical. However, when we look at UG level education, the situation is quite different. There are only very few adventurous institutions where BIM is already a part of their curricula, albeit quite disintegrated from the rest of the more conventional content and methods of delivery. BIM integrated design studios have also become a rather experimental and safe option in the introduction of BIM into the curricula, which are implemented in both UG and PG level studios. In most cases, architecture students work in "collaborative design teams" pretending to be another disciplinary member of the design team. In few cases, students from different disciplinary backgrounds are brought together to collaborate on design/engineering challenges. In both cases, the studio is quite isolated from the rest of the curriculum and the chosen approach doesn't follow any particular institutional and pedagogical agenda. Determining the success criteria for these experiments are also quite challenging due to differences between the maturity levels of students, their varying familiarity with the software used, and the focus of the studio challenge.

A recent article examined 3 integrated studios that variously explored designs (design collaboration, formal possibilities, engineering integration into design) and how they adjusted to the protocols of BIM, each providing interesting and contrasting examples (Pihlak et al., 2011). Some of the key findings of this study can be summarized as follows:

1. BIM teams that strived to minimize the conflict produced the least innovative designs,
2. The collaboration across different disciplines seemed to be productive when designers were strong and confident and when the engineers were flexible enough to go along with the non-linear creative process,
3. Too much compromise led to less than optimal design solutions,
4. The design went into the direction of the discipline where there was more confidence,
5. Design emphasis could easily get lost in an expanded field where numbers, time and money are so present.

A FRAMEWORK FOR BIM INTEGRATION INTO ARCHITECTURAL CURRICULUM

BIM is not just a new topic to be added to the existing curriculum, as it currently is being implemented by many schools, being introduced to the students either as "a new technology" in the studio, and/or as a "new topic" in the professional practice modules, mainly towards the end of the Bachelor level education with not much real connection with the rest of the curricula. If the concept of "BIM and integrated design" is to be embedded into Architectural education, this needs to be a gradual and progressive integration, instead of an "add and stir" approach. It needs to be connected with the rest of the curriculum, and we must be able to make sense of this new method and technology in a continuum, and by identifying our frames of references in relation to how things were in the past, how they are now and how they are changing with new tools and working methods. In order to collaborate, we have to be even more confident and competent in our ability as architects and understand the capabilities and potentials of BIM for our own profession and the design team, and influence the direction of BIM as such. We need to understand the viewpoint of the "others" instead of acting like them. Therefore we propose two core modules that need to be delivered already at the undergraduate education (Part 1 in UK Schools) starting from year 1, progressing in complexity and content as the student matures, and with an increasing degree of integration with the design studio; *Modelling and Representation* and *Collaborative Working*.

Modelling and Representation

The intelligent modelling approach, advocated by recent digital design media and BIM technology are fundamentally changing the way architects used to produce and communicate design information. In architectural education, the reproduction of the "drawing" has a special focus. The fundamental change BIM introduces is the separation of the representation and content; information in models can be viewed using different representations for different purposes and audiences. Thus, there is an urgent need to shift the focus from "drawings" to creating "intelligent" models of the design (including the possibility to generate drawings from the model). As Hugh Whitehead eloquently put it, design requires a "federation of models' (Whitehead et al., 2011) at different levels of abstractions at different phases of the design. Thus, a sketch is a model, but with a high degree of abstraction. A physical model, is yet another.

Heavy emphasis on "drawing" has also brought about "layered thinking" in terms of scales. So the level and detail of thinking has almost become restricted to the scale. Although scaled drawings can be produced from BIM models, certain information has to be thought through quite early in the process and embedded into the model. A core module on "modelling and representation" should convey the fundamental understanding of how various tools and techniques help designers model different types of information, on different level of detail in different stages, and the degree to which they influence and affect the design thinking and process. There are other motivations to develop representations as well, for example, “how to sell your ideas”, “how to effectively communicate the value in your design”, etc. There are different ways of embedding value and information into a design through different levels of abstractions and different types of representations according to “who” you are dealing with and “for what purpose”. However this variety has not been sufficiently present (or encouraged for that matter) in Architectural Education. A majority of schools still require a pre-determined set of scaled drawings for the final studio presentations which are prepared usually for the eyes of other designers, whereas in real practice, architects communicate and negotiate information across a much wider community of professionals and clients, who seldom can fully understand traditional drawings. What we are proposing is a shift of emphasis from the final product representation towards the process of design creation, development, coordination, communication and negotiation through representations. In such a discussion, we implicitly define the role we think the architect should play in the future. Does the architect’s role end by preparing the right type and format of information, or do we want to coordinate this multi-layer information web?

The student learning in this module should progress from understanding the fundamentals, then developing intelligent models, and then selectively sharing and exchanging information in data-rich models. Students should also be able to understand the underlying concepts of *creative* and *operational modelling* and the degree of abstraction, clarity and precision required in both.

Collaborative Working: Tools, Issues and Methods

The appreciation of the differences in professional, disciplinary and cultural values during collaborative working has become an important concern with an increase in global mobility and global practices. We propose a core module in “Collaborative Working” that explicitly clarifies the role of architects in a larger community of built environment professionals and introduces the various tools, issues and methods that are geared toward varying goals and practices of collaborative working. As the students get more mature, they should be exposed to diverse set of tools, methods and techniques with which they can experiment, compare and appreciate the differences between individual and collaborative working in different design exercises.

A common tendency in BIM integration in architectural education today is the introduction of “multidisciplinary” design studios, as discussed in the previous sections. Although it is useful to mimic the actual design practice by bringing students from different disciplines together (each drawing on their disciplinary knowledge) at certain point in their formal education, the timing of such an interaction is of vital importance and could only be useful if the students have already gained a certain degree of maturity in their own specialization. In order to make this point clear, we refer to Marilyn Stember’s paper (1991) where she offers the following overview of different levels of disciplinarity (descriptions are summarized to fit into our context).

- Intradisciplinary: working within the professional boundaries of a single discipline.
- Cross-disciplinary: a design team (or an individual designer) from one discipline is viewing and using concepts of another discipline from the perspective of their (his/her) own.
- Multidisciplinary: people from different disciplines are present and working on the same project, however each one is operating on their own disciplinary knowledge
- Interdisciplinary: a design team (or an individual designer) is integrating knowledge and methods from different disciplines, using a synthesis of approaches.
- Trans-disciplinary: a unified and commonly accepted framework (understanding) beyond any individual disciplinary perspectives of a community of practice

Architectural education needs to address all of these levels of disciplinarity. Design is intrinsically an *interdisciplinary* activity as the design process entails a continuous synthesis and negotiation of different knowledge from different disciplines. However, this requires an awareness of our own disciplinary roles and responsibilities (*intradisciplinarity*). Only with this awareness, we can utilize the knowledge of other disciplines, appreciate the role they play in relation to ours (*cross-disciplinarity*) and be able to draw on our own disciplinary knowledge in a confident way and can make an effective and creative contribution in a *multidisciplinary* context. When these concepts are used as pedagogical approaches, they are all valid and necessary at different stages of architectural education (and training). However each requires a different level of maturity (of students), and a brief (on an appropriate scale) to support the intended outcome of the relevant studio or taught module it's applied in. Similarly, one should also pay attention to the suitability of each method in different context. For example, interdisciplinarity and cross-disciplinarity are more appropriate for creative design, and multidisciplinarity is more appropriate for relatively more mature students. For example pairing architectural students with engineering and construction management students in "integrated BIM studios" in the early years of UG design education would be "pedagogically incorrect" if the students are not yet at a maturity to recognize each discipline's own values, procedures and protocols. Students would still learn useful skills but this would most probably be at the expense of the quality of the design outcomes as design emphasis would most probably be diminished. It would probably make more sense to introduce "intradisciplinary" and "interdisciplinary" studios during early and later years of UG education, respectively, and "multidisciplinary" studios at the PG level, when the learners have the necessary maturity. Trans-disciplinarity is still an undefined territory in design and construction. Some of the concepts advocated by "integrated design" are currently being recognized as trans-disciplinary. However, this should not be seen as a casual blurring of disciplinary boundaries. On the contrary, as emphasized eloquently by Hanif Kara, one of the conditions of a successful "integrated design" is that "each discipline should become more skilled at what they do and, most importantly, respect and value the contribution of each other as a first step towards new working processes" (as cited in Pihlak et al., 2011).

COGNITIVE IMPLICATIONS

These recent trends in "digital media and BIM integration" in collaborative design studios point out to a common tendency across many schools of architecture; aiding the learner development through both social and technological scaffolds. In this respect, we identify the emergence of a dominant 'tool-aided', 'socially shared', contextual and highly situated forms of cognition commonly referred to in literature by developmental psychologists and learning theorists as "distributed cognition" (Hutchins et al., 1986) and "distributed intelligence" (Pea, 1993). The central idea is that the resources that shape and enable activity are distributed in configuration across people, environments, situations and artefacts (tools). One of the main pedagogical dilemmas today can be grounded on the gap between the distributed and the individual levels of intelligence that students are building through diverse methods of knowledge acquisition and methods of delivery without any explicit recipes of how to build the link between the two. This separation has become even more distinct with the integration of technology and collaborative working methods in the design studio.

Salomon (1993) introduces two kinds of cognitive effects of technologies on intelligence:

- **Effects with** technology is obtained during intellectual partnership with it, and
- **Effects of** technology in terms of the transferable cognitive residue that this partnership leaves behind in the form of better mastery of skills and strategies.

While **effects with** refers to the development of Distributed Cognition, **effects of** is attributed to the development of individual cognition and solo intelligence which are essential for the learner to develop an autonomous response as a residue to interaction with the social and technological scaffolds. Today, the special emphasis on the use of a variety of BIM software and skill building workshops offered by many tool builders provide mainly technical scaffolds to the learner. This disproportionate emphasis placed on the "tools" present a risk of promoting design and collaboration as solely a tool-driven activity, especially for the novice learner, displacing the innermost values of architecture, and as a consequence, weakening and changing the role of designer in the society (Kocaturk et al., 2012). In sum, we propose the development of individual and distributed competencies within the same pedagogical framework.

SUMMARY AND DISCUSSION

The article gave a critical overview of some of the fundamental issues regarding the adoption and integration of BIM – both as a method and as a technology – in Architectural education. It also tried to explicate some of the fundamental reasons for the current resistance while reflecting on the past and present state of the cultural, intellectual, professional and technological context of Architecture. A critical review of some of the existing educational approaches to BIM integration, such as BIM integrated studios, revealed the fact that the current implementations are quite opportunistic, disintegrated from the rest of the curriculum and lack any clear strategic and/or pedagogical agenda. Two major areas have been identified where BIM will have direct impact on the architectural curriculum; 1) modelling and representation, and 2) collaborative working. These areas have been proposed to be added to the architectural curricula as the two new core modules, starting from year 1, and progressing in complexity and content as the students mature, with an increasing degree of integration with the design studio. Some of the critical pedagogical and cognitive issues have been identified according to the extent to which the new technology and working methods will have an impact on the process of learning and development of both individual and distributed cognition.

It is also important to note the changes in the professional services provided and required from the architects, on a global scale. We are experiencing the emergence of additional profiles, new specializations and consultancy services high in demand in building industry. In such expanded modes of practice, one size doesn't fit all. Is it sustainable or even possible to reproduce "architects" with exactly the same profile? New specializations (such as BIM Manager) should be introduced to students as possible (alternative) pathways already during their UG education, which they could later choose to specialize on during their PG studies. This might be influential in harnessing the most out of individual talent and interest (e.g. design, technical skills, business).

Will architectural education just follow BIM as a trend, solely as a beneficiary, or become one of the driving forces in this industry transformation? Do architects really have the chance to renegotiate their status and maybe even regain their master-builder status with BIM – as implied by many – or does BIM further emphasize and legitimise the hybridity of architectural profession? The answer to these questions, for each and every architectural institute in particular, will be the main guide in setting up a plan for their interpretation and integration of BIM in their educational agenda with relevant and necessary technical infrastructure and pedagogical approaches. And there is a good indication that there will be parallel and contrasting approaches across institutions, which ultimately will determine a new plural agenda for the profession. Therefore the underlying challenge is about renegotiating architects' multiple identities and redefining the problematic relationship that has long existed between academia and practice; techniques and aesthetics; science and humanities.

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Attaining Performance with Building Information Modelling

A systematic literature review of product and process modelling in AEC

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Abstract. *The paper presents the findings of a systematic literature review of approximately 200 scientific sources. It is designed with the aim to identify the current benefits and factors of high performance in Architecture, Engineering, Construction (AEC) since the introduction of Building Information Modelling (BIM). We formed and confirmed two main propositions associating the performance of the AEC to the use of BIM. The mapping of the current impact and benefits of BIM showed that the role of the managers, suppliers, owners and authorities is underestimated, as well as the initiation and use stage of project development. At the same time, the performance in the AEC industry can be improved by an array of possibilities where IT research and policy-making authorities contribute – from establishing new collaboration protocols until improving existing or creating new BIM tools.*
Keywords. *Building Information Modelling (BIM); Architecture, Engineering and Construction (AEC); supply chain management; life-cycle phases; stakeholders.*

INTRODUCTION

Performance in architecture

The idea of performance in architecture has been extensively debated during the last years, in example in the "Performative Architecture" symposium organized in 2003 by Kolarevic and Malkawi (2005). Discussion has focused on the "apparent disconnect between geometry and analysis" despite the variety of the available digital tools (Kolarevic and Malkawi, 2005) and on performance perceived as a qualitative criterion in architecture. For the recipient of the built environment and the critical thinker, performance is an objective quality measure, which offers rationale and clarifies the multiplicity of current approaches and phenomena in architectural artefacts.

Performance is an important consideration in many other industries, ranging from education to commerce. For example, terms such as Performance Indicators or Key Performance Indicators – although still a jargon from industry that lacks clear definition – are "items of information collected at regular intervals to track the performance of a system" (Fitz-Gibbon and Tymms, 2002). From this perspective, performance is also the success factor in design. The design process and the design object are the two sides of the same coin. Yet, in architecture, arguably due to the subjective input of the designer, performance is neglected and the emphasis is on the aesthetic qualities of the architectural object. But yet again, when performance becomes a serious consideration in architecture, it is generally restricted to the performance of the design product, the artefact, the building. Little is being researched over the performance of the design process and its significance for the quality of the product.

Until recently Computer Aided Design (CAD) software was the basis of computerization in architectural practice and its use portrayed the contemporary architectural process (Aouad, 2012). The introduction of Building Information Modelling (BIM), approximately ten years ago (Eastman et al, 2008) and its broad settlement as an integrated interdisciplinary design environment (Deutsch, 2011); suggests significant changes in not only the representation of the design product but also in the structure of the design and construction processes.

Authors' approach

The advancements in technology, in both software and hardware engineering (programming, computing and networks) have resulted in a variety of solutions that gradually ameliorate the status of the field. BIM technology – approach or process – is an object-oriented modelling tool that contains 3D data with "parametric intelligence" (Eastman et al, 2008). In design theory, BIM is seen as an evolution of pre-existing technologies and approaches including CAD and product modelling. This attribute adequately covers the product aspect of architecture. On the other hand, BIM is a recent arrival in construction and design management, i.e. the process side of AEC. In addition to being a design tool, BIM is also a powerful management tool (Hardin, 2009).

Currently, there is still a lot of room for theory building on how exactly BIM and management can collaborate towards the achievement of an integrated approach in architecture. This statement coincides with the position of the authors. Thus, the approach of BIM from our part is nor technical, nor in terms of design, but from a design-and-construction management point of view and particularly from a supply chain (SC) perspective. AEC has a "highly fragmented" structure (O' Brien et al, 2009). Due to the lack of collaboration and coordination between the different organizations that participate in the industry, its contemporary image is of low performance. We define performance as the maximum proportion of output to input. The four theoretical perspectives of approaching the building SC are economy, organisation, social and production perspectives (Vrijhoef, 2011). Originating from these four SC perspectives, we categorised ten focal points – interrelated but loosely clustered – from which to research BIM (Figure 1) through a "construction SC management" conceptual lens.

Research question

The main inquiry of the paper is the impact of BIM in the performance of AEC industry from a supply chain perspective. First (Q1), which exact phases and actors of the AEC currently receive more benefits from the application of BIM? This investigation will identify the positive performance of BIM in certain phases and stakeholders. The reverse argument identifies

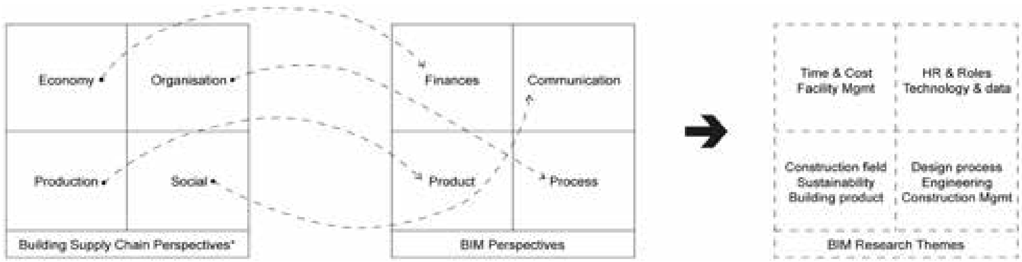

Figure 1
Foci for researching BIM (adapted from Vrijhoef, 2003).

the neglected – or less researched – phases and actors during the development and employment of BIM applications. Second (Q2), which specific features of BIM improve the performance of AEC industry throughout the whole supply chain and how?

The study addresses both the professional and academic side of the field, given that knowledge form practice and theory is interchangeable in the engineering domain. Our goal is to reconsider the ways we can achieve the performance required by contemporary architecture and the built environment by illuminating the benefits of applying BIM in architectural projects and identifying gaps in literature and theory. At the same time, the authors consider performance in suggesting a system of actions for the management of architectural projects.

METHODOLOGY

This paper uses a qualitative approach and performs a quantitative or quantifiable analysis on a merely qualitative material, in this respect the bibliographic material. Traditionally case studies are the norm in conducting research into the performance of a process. Indeed, case studies offer a variety of qualitative results with inductive character and deep understanding of the research problem. Unfortunately, a case study produces a local, specific and project-driven knowledge output that is difficult to be generalised into the performance of other systems. The output is often limited to the interviewees' or the researchers' point of view. On the other hand, a wide bibliographic research offers a spherical coverage in actors, phases and processes, which is after all the focus of the managerial perspective. These two methods (case study and literature research) are better to be considered as complementary rather than rivals in designing a research.

At this point, it is important to clearly position this paper in its scientific context. As mentioned before, it follows a managerial perspective concerning the impact of BIM in the performance of AEC. Since the managerial perspective in this case is focused on SC management, it is crucial to categorise it according to this research approach. There are five types of research design for a supply chain study: substantive justification for theory building, surveys in SC management, case study research in SCs, action research in SCs and modelling SCs (Seuring et al, 2005). However, there is no right or wrong as to which method to choose – descriptive or empirical – as long as the scope is clear and its application adequately employed.

Literature review has proven to be a very useful tool for both qualitative and quantitative studies. Among others, a literature review provides a framework for establishing the importance of the study and relates it to the larger on-going discussion. In this case, the proposed methodological tool is a "*systematic quantitative literature review",* a tool originating from ecology and environment sciences. It offers an overview of existing approaches and "by mapping the literature it is possible to highlight the boundaries around generalisations derived from the literature" (Pickering and Byrne, (In Press)). The literature review described here acts as a big variance data entry method. This paper is the report of only one component – due to paper length limitations – of the larger systematic literature review that was conducted between February and June 2013. The findings that are presented here are content-related preliminary findings of the whole study.

DATA COLLECTION AND DISPLAY

Collection of the material

The primary material comes from scientific sources and has no commercial origin. Periodical scientific texts or other sources that require a short time interval between the development and the publication of the research are the main material of this study. Comparing such material to books, they capture a more genuine and dynamic – although sometimes raw or incomplete – state of the research in time. Consequently the selection of the material is limited to peer reviewed material such as journal articles and conference papers.

Throughout the literature, the term *Building Information Modelling* or *BIM* appears from 2002 onwards mostly in commercial publications but it is only around 2006 that the subject starts to become a research object in scientific publications too. The total number of scientific source on *Building Information Modelling* or *BIM* during 2006-2013 according to Google Scholar (assessed on May 6, 2013) is 5010, where the key terms appear in the body of the text, and 344, where the key terms appear only in the title. In order to emphasise on the material that is indeed relevant to BIM, the appearances throughout the body of the text are considered of minor importance, since the term BIM may be only mentioned in the "discussion" or the "reference" sections of the source. At the same time in Scopus database (assessed on May 6, 2013), which does not hold a global coverage in journals and conference proceedings, there are 272 sources and our topic appears on the title, the abstract or the keywords. All the afore-described steps are quantifiable and repeatable.

Display of data

The collected material complies with the main research context, which is BIM in the AEC industry from an academic and an industrial point of view. Of course a sort of bias may be applied in the selection of the material, since selecting a sample of 272 or 344 sources allows the subjective character of the research designer to interfere. The inability to include material for reasons such as copyright and accessibility was the only limitation in this process. Since the resulted collected sample of 198 sources was not too large, no special sampling strategy was used. The failure to include the rest of the material was considered random. Aiming to explore the potential of BIM (as a process or a tool) from a managerial perspective, the research focuses on ten sub-themes: time & cost, facility management, design process, engineering & consultancy, construction management, construction field, sustainability, building product, human resources & roles and technology & data.

The selected material is analysed and categorised in order to answer the questions posed in the introduction. After the analysis, each scientific source provides a data set with information. The data collection method uses computer-assisted survey information collection software, i.e. an online survey tool. An evaluation form designed as a questionnaire collects and displays the data. The questionnaire has a three-part skeleton composed of a descriptive part (basic information), an analytic part (focus on the content and the quality) and a conclusive part (epilogue and recap). The first two parts of the evaluation form are designed in a quantitative manner with closed questions in order to categorise the sources and communicate the findings as much objectively as possible. The third part contains open questions and accumulates qualitative data. From these two types of data only the quantitative – first two parts – are presented and discussed in this paper.

DATA ANALYSIS AND RESULTS

Analysis of data

The data collected from the evaluation forms of the selected material underwent a two-level analysis. The first level involved the semantics of the scientific texts. It included data in relation to the characteristics of the publication and the categorisation of the primary author (Table 1). The second level concerns the pragmatic content of the sources focusing on the overview level as well as quality assessment of the sources. The main findings are presented in the second and third table (Tables 2 and 3). Descriptive statistics have been used to summarise the data in a shorter form. Since most of the variables are qualitative or categorical, the mode – or else the frequency measure – of the sample is the most important and usable measure that can be applied to all variables regardless their type.

Findings

The raw findings are presented in the three tables. Table 1 presents certain attributes of the scientific sources in a condensed form. Both the number of publications and percentages are stated here in order to present an overview of the origins of the existing research material on BIM. Table 2 gathers the mentions of BIM benefits. We categorise and corre-

Table 1
Condensed results from first level of analysing the scientific sources on BIM in absolute and relative units.

Characteristics of scientific sources on BIM	Sources	Frequency (%)
Primary author with background from academic research	161	81.31
Primary author with background on Construction Management	60	30.30
Primary author with senior expertise in industry or academia	136	68.69
Research based on case studies	126	63.64
Global applicability of the research	159	80.30
Research published in scientific journals	105	53.03

late these benefits according to the project phases of AEC and the actors participating to it. Table 3 collects the benefits from using certain BIM features categorised under the relevant SC research perspectives.

Results

Most of the publications on BIM (81.30%) have been authored by researchers originating from the academia (Table 1). A number of these researchers is also active in industrial organisations. Construction

Table 2
Benefits from using BIM per actor of the AEC industry and project phase in absolute numbers of the sources.

BIM benefits (Number of references in the sources)	Architects	Managers	Engineers	Consultants	Contractors	Suppliers	Owners & FM	Regulatory Authorities
Initiative	53	43	35	22	29	12	26	21
Design	124	78	107	52	64	20	42	30
Construction	54	57	74	29	65	27	27	20
Use	16	27	23	17	15	13	48	16

Table 3
BIM features and SC research perspectives correlation derived from the literature in absolute numbers.

BIM features (Number of references in the sources)	Feasibility tools	Contracting tools	Specification tools	Preliminary massing	Visualisation	Collaboration tools	Clash detection	Mechanical tools	Environmental analysis	Cost estimation	Direct fabrication control	Construction scheduling	Quantity take-off	Facilities management
Time & cost	32	14	22	5	16	22	28	12	8	33	10	35	11	6
Facility mgmt	6	2	16	5	11	15	12	10	13	5	5	5	0	18
Design process	31	24	46	27	87	58	44	18	28	24	16	18	11	15
Engineering	22	18	31	12	38	37	34	23	15	16	14	23	10	6
Constr. mgmt	20	24	27	7	23	43	23	8	4	21	14	44	11	5
Constr. field/site	11	17	23	7	20	20	19	13	3	15	12	30	10	5
Sustainability	13	0	5	1	9	9	9	1	20	6	2	2	0	5
Bldg product	13	6	17	3	18	22	9	7	18	8	3	6	2	13
HR & roles	8	9	7	4	12	31	12	0	3	4	3	6	1	7
Technology & data	13	12	49	8	40	40	30	20	18	15	14	24	8	14

BIM benefits (%)	**Architects**	**Managers**	**Engineers**	**Consultants**	**Contractors**	**Suppliers**	**Owners & FM**	**Regulatory Authorities**
Initiative	**26.77**	21.72	17.68	11.11	14.65	*6.06*	*13.13*	10.61
Design	**62.63**	**39.39**	**54.04**	**26.26**	32.32	*10.10*	21.21	**15.15**
Construction	27.27	28.79	**37.37**	14.65	**32.83**	**13.64**	13.64	*10.10*
Use	*8.08*	*13.64*	*11.62*	*8.59*	*7.58*	6.57	**24.24**	*8.08*

Table 4
Summary of references on the actors and phases of the AEC industry benefited from BIM.

managers have authored 30.30% of the research on BIM. This element strengthens our initial proposition that BIM is considered more as a tool to achieve an occasional high performance, rather than as a permanent project management tool or a process to be used towards the integration of the construction supply chain. At the same time, the fact that not only junior but also a lot of senior researchers are keeping busy with BIM reveals that they are already convinced about its potential and the impact and are committed to put their expertise in action. The majority of the publications (63.64%) use case studies and experiments to validate their hypotheses.

Table 4 contains the data of Table 2 in percentages and indicates with **bold** the number of sources where the actors and the phases experience more benefits from the employment of BIM and with *italics* where the actors and the phases profit less. Apparently (A1) the architects and the engineers are the actors who are either the participants more involved in the research and adoption of BIM – or are simply considered the primary actors – in BIM literature (Table 4). Surprisingly, construction managers are not equally prominent to these primary actors, as one might have expected but they are more involved in all phases of a project, while contractors are referred to mostly in the construction phase. Suppliers are also referred in the construction phase but are limited to peripheral roles in the rest of the building life-cycle. On the other hand, owners and regulatory agencies seek immediate involvement but achieve only fragments of presence mostly during the initiative and use stages.

Table 5 emphasises with **bold** the mentions of the most prominent BIM features and with *italics* of the most underused. The aim here is to indicate the features of BIM that improve the performance of AEC industry throughout the whole supply chain (A2). According to the literature review, BIM features such as visualisation, clash detection and collaboration tools are the most researched by far, which on the one hand increases the performance of the building product but on the other hand contributes to the performance of AEC only incidentally. For instance, quantity take-off and facility management tools – employed mostly for facilitating the suppliers and the owners respectively – are either neglected for certain research perspectives or only appear in the 6 to 9% of research into BIM. Likewise, while there are tools for the construction field, such as direct fabrication tools (Table 5), they are seemingly not widely applied or reported. Other BIM features mentioned but not included here are laser scanning and tools for safety on the building site.

DISCUSSION AND CONCLUSION

Discussion

The research design answered sufficiently the research questions. Comparing this research to other studies, the most apparent difference is to be found in the methodology. Identifying benefits and quantizing performance via literature review is not the norm in this domain. The present research shares common concerns and limitations as publications based on case study research. Comparing it with

Table 5
Summary of correlations between BIM features and SC research perspectives.

BIM features (%)	**Feasibility tools**	**Contracting tools**	**Specification tools**	**Preliminary massing**	**Visualisation**	**Collaboration tools**	**Clash detection**	**Mechanical tools**	**Environmental analysis**	**Cost estimation**	**Direct fabrication control**	**Construction scheduling**	**Quantity take-off**	**Facilities management**
Time & cost	**16**	7	11	*3*	8	11	14	6	4	**17**	5	**18**	**6**	*3*
Facility mgmt	*3*	1	8	3	6	8	6	5	7	3	3	3	*0*	**9**
Design process	**16**	**12**	23	**14**	**44**	**29**	**22**	9	**14**	12	**8**	9	**6**	8
Engineering	11	9	16	6	19	**19**	17	**12**	8	8	7	12	5	*3*
Constr. mgmt	10	**12**	14	4	12	22	12	4	*2*	11	7	**22**	**6**	*3*
Constr. field/site	6	9	12	4	10	10	10	7	*2*	8	6	**15**	5	*3*
Sustainability	7	*0*	*3*	*1*	*5*	*5*	*5*	1	**10**	3	*1*	*1*	*0*	*3*
Bldg product	7	3	9	2	9	**11**	5	4	9	4	2	3	*1*	7
HR & roles	4	5	4	2	6	16	6	0	2	2	2	3	1	4
Technology & data	7	6	25	4	20	20	15	10	9	8	7	12	4	7

previous studies, it focused on the performance of the AEC process via the use of BIM rather than "discussing how information systems can further contribute to this research domain" (Merschbrock and Munkvold, 2012). There are again limitations over how exactly to measure performance, a problem already mentioned in other studies (Barlish and Sullivan, 2012). A solution to this problem is be the classification of benefits as having a positive or a negative impact, as suggested in research on case studies (Bryde et al, (In Press)). Apart from sharing common concerns and limitations with existing researches, the present study has the dual advantage of including all the involved participants in the AEC industry and referring to all the stages of the AEC.

Although the findings presented here do not cover the full extent of the research conducted – due to paper length limitations – the main results already suggest concrete directions for further use. From the summarising tables in the results section (Tables 4 and 5) we indicate certain directions that require further attention and investigation (Figure 2). Undoubtedly, with the still rapidly evolving state of the information age, research directions in the field may change day by day. However, this study has showed that there are certain neglected research areas and correlations that arguably explain the low performance of the AEC industry. The content of this paper offers a guide to improving the behaviour of the neglected project phases and actors by integrating the construction supply chain. Concerning the methodology, the research adds on how to conduct literature research with an eye not only in the semantics and external characteristics of the scientific material but also in the overview level of the scientific material. The present method could also be employed in the future by either focusing on a narrower research field or including certain types of publications. Lastly, anticipating the criticism over the credibility of a literature review, we defend the selection of this research design by restating the quality assessment that was incorporated during the employment of the experiment.

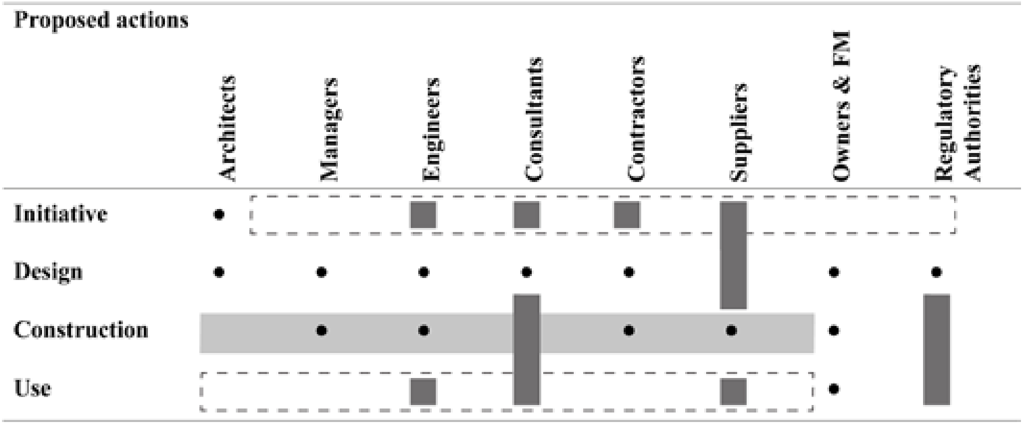

Figure 2
Proposed action framework for BIM research (Horizontal stripes: Collaboration protocols, dark grey: IT tools).

Conclusion

The study described in this paper identified the life-cycle phases and stakeholders who experience more benefits from the current application of BIM and thus are considered high performance parameters for the industry. On the other hand, the phases and stakeholders who are either neglected or simply left behind in the adoption of BIM are of low performance and may be subjected to future research. The research also revealed the BIM features that are currently used more extensively and the BIM features with low applicability of popularity in a sense.

Using the most and the least benefited from BIM actors and AEC phases (as indicated in Table 4), we identify gaps not only in the performance of the participants, but also in the performance of the various processes that take place during a project. For example, in the initiative phase, only the architects are adequately involved, while they are less involved – along with all other actors apart from the owners – in the stage of end-use. On the other hand, in the design phase almost all the participants – with the exception of the suppliers – are equally benefited from the implementation of BIM, whereas in the construction phase there is a continuous fluctuation in regard to the involvement of the actors (Table 4). At the same time, Table 5 reveals that preliminary massing, direct fabrication control and quantity take-off are the most underused tools.

Combining the research results from Tables 4 and 5, we propose a framework towards a highly performative AEC industry (Figure 2). New and stronger collaboration protocols between the managers and the owners should be implemented in the initiative phase, and likewise appropriate collaboration protocols should be applied in the use stage of AEC (dashed horizontal stripes). The employment of supply chain integration in construction aims to regularise and enhance the involvement of all actors in this stage and at the same time improve the performance of the AEC (light grey horizontal stripe). We also argue that the underused BIM features should be extended or improved in order to serve the involvement of all the stakeholders in the AEC process (dark grey stripes).

Finally, we observe that while the role of the architect is being given adequate attention in BIM research and adoption, the role of the manager is not equally emphasised. The existence of many and various BIM features arguably makes as the manager an integrator of the whole process rather than merely another BIM-user. To conclude, apart from reaching our own research objectives, the present study forms a roadmap for fellow researchers interested in the domain of BIM by revealing subjects for further exploration.

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Building Your Own Urban Tool Kit

Utilizing parametric BIM components as smart early design tools for large-scale urban planning

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Abstract. *The paper describes the development of a set of smart BIM components to facilitate and accelerate the creation of large-scale urban models in the early design phase in a BIM software environment. The components leverage the analytical, parametric and modelling capabilities of the BIM environment to support adaptive parameter-driven building geometry, patterning of different building types, early numerical and graphical design evaluation, various simulation methods and the exploration of design alternatives. The toolset consists of the most common building shapes, but can be extended with additional shapes and their respective area and volumetric calculations when necessary. The rapid large-scale deployment of the components has been achieved by diverting existing tools from their intended use.*
Keywords. *BIM; urban planning; early design; rule-based design; parametric design.*

PROJECT CONTEXT: BIM VS. GIS.

Building Information Modelling (BIM) is quickly becoming the de-facto standard in the computer aided design and documentation of buildings, albeit with varying adoption rates in different world regions (McGraw-Hill Construction, 2010 & 2012). Data structures in BIM applications can be described as semantic, parametric and component-centric (Eastman et al., 2008). BIM applications utilize the Industry Foundation Classes (IFC) file format that was first released in 1996 (Bazjanac and Crawley, 1997) for the exchange of semantic data models.

For the urban scale, similar efforts to create a semantic data model have been made with CityGML (Gröger and Plümer, 2012). Although, compared to IFC, CityGML is a relatively young data format (Kolbe et al., 2005), it is supported by a growing number of commercial software products [1]. At present, however, none of these are BIM applications (and are thus located outside of the "comfort zone" of architects), but the issue of interoperability between building and city models has become a hot topic of research in recent years (Nagel and Häfele, 2007; Isikdag and Zlatanova, 2009; El-Mekawy, 2010; De Laat and Van Berlo, 2011). Therefore it stands to reason that in the foreseeable future BIM applications will gain the capability to author semantic urban models.

The parametric and analytical capabilities of BIM applications have proven to be somewhat useful for urban design in the past (Miller at al., 2009) and research has been conducted towards the implementation of zoning requirements in building information models (Donath and Lobos, 2006; Kim et al., 2011). However, with increasing project scale, the mere process of placing a large number of diverse elements, altering their attributes and exploring design alternatives has left much to be desired with regard to speed and usability.

REQUIREMENTS FOR A SMART TOOLBOX

The focus of the project was to create a toolbox of smart components that could be used as generic building masses inside a BIM application for large-scale urban planning projects. Building models in urban design projects are usually made up of a limited number of building archetypes, yet each building instance has to accommodate the geometric conditions and zoning requirements of its respective parcel as well as the overall design intent. Additionally, there is a strong need for evaluation, especially in the early design phase, in order to facilitate informed decision-making. Hence, the following requirements were set for the components:

1. A large number of components can be distributed rapidly in a given spatial framework, making it possible to create a large-scale urban model in a fairly limited amount of time.
2. The components can adapt to varying lot sizes and geometries.
3. The components allow for the rule-based parametric generation of building forms according to zoning requirements.
4. The components can accommodate different terrain conditions, i.e. they work on level and sloped terrain surfaces.
5. It is possible to automatically or at least semi-automatically place components in patterns (such as ABAB etc.) to allow for variations in the design.
6. The components can instantly report most if not all essential numerical information relevant in a typical urban planning scenario such as areas, volumes etc. but also, if possible, some statistical data on costing or environmental impact (e.g. CO_2 footprint).

In turn, the requirements for the host application itself were defined as follows:

1. Allow for the creation, distribution and maintenance of components according to the requirements listed above.
2. Generate tabular reports of component attributes.
3. Allow for visual filtering based on component attributes.
4. Facilitate the creation and comparison of design alternatives.
5. Possibly even provide additional analysis tools.

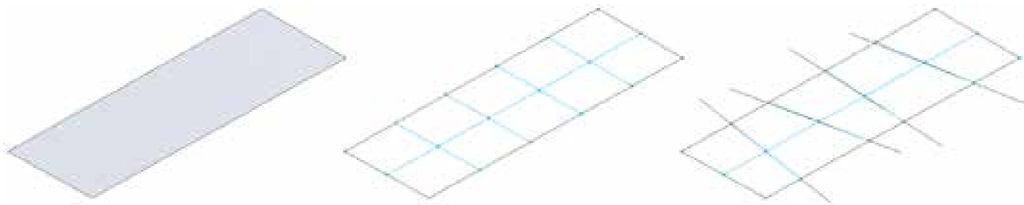
Based on the above requirements, Autodesk's Revit platform [2] was chosen as host application. Not only does it meet all the requirements, but its conceptual modelling application Vasari [3] also includes analysis tools for environmental factors like sun and wind.

DESIGNING FOR RAPID DISTRIBUTION

Repetition and variation are common concepts in architecture. They can be easily identified in building elements such as curtain walls, staircases, railings, structural systems etc. BIM applications generally provide dedicated tools for these types of building elements. The same concepts of repetition and variation apply to urban planning as well, perhaps with a special emphasis on the adaptability of buildings to the geometric conditions of their respective parcels. However, there are no dedicated tools for distributing a large number of building masses in a typical BIM application. Therefore, the approach was to divert tools readily available in the chosen application from their intended use.

With the 2010 version of Revit, Autodesk introduced a new conceptual modelling environment that was intended for the modelling of building masses [4]. The potentials of this modelling environment were described by Miller et al. (2009), but the workflow outlined by them involved the manual modelling of each building (or at least manual changes to placed building instances). The 2010 version did, however, come with another functionality

Figure 1
From left to right: a) Mass surface, b) Automatic subdivision, c) Manual subdivision.



with a lot of potential regarding the adaptability of a large number of objects to varying geometric conditions: Mass surfaces could be rationalized by using the "divide surface" functionality and subsequently be populated with "pattern-based curtain panels". Revit 2011 saw the introduction of the "adaptive components" functionality: placement point based components that can adapt to varying spatial conditions [5]. Lastly, with the 2013 version came the "repeat and divide" workflow that can be used to create more complex arrays of objects (Dieckmann and Kron, 2012) and facilitate the large-scale distribution of reactive components ("reactors") as described by Woodbury (2010).

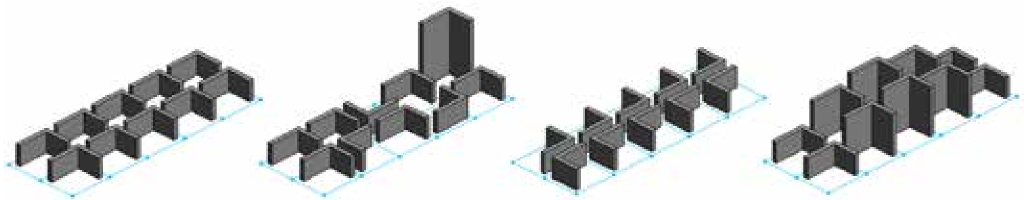
Surely none of these functionalities were designed with large-scale urban planning in mind – most of them are typically used for the creation of curtain wall systems and other building elements – but they can be "abused". In the context of the project, the aforementioned tools are used as follows:

1. The footprints of city blocks are created as mass surfaces (Figure 1a).
2. These mass surfaces can then be subdivided into lots using the divide surface functionality, creating a grid within the city block. The grid can either be generated automatically (Figure 1b) using a layout algorithm (e.g. number of subdivisions in U/V direction) or manually (Figure 1c) by drawing a number of lines to generate the subdivisions.

The actual toolbox consists of several types of building masses created as pattern-based elements and adaptive components that can be hosted on and rapidly distributed across divided surfaces. Depending on the desired outcome, two separate modelling strategies can be applied for populating the grid with the building masses:

1. For a simple pattern, the divided surface can be assigned a pattern-based component (Figure 2a), essentially distributing instances of the same building block across the entire grid of a block. Exceptions can be defined by selecting individual instances and manually switching their type or altering their instance properties (Figure 2b).
2. More complex patterns of several alternating building types can be created as one or two dimensional arrays by employing the repeat and divide workflow (Figure 2c). In addition, this workflow allows for the rapid deployment of context-aware adaptive components that can, for instance, react to the proximity of other objects in the model (Figure 2d). A common application for this method would be the increase of density towards certain zones in the urban model (see below).

Figure 2
From left to right: a) Divided surface populated with pattern-based components, b) Manual exceptions, c) Patterning with divide & repeat functionality, d) Reactor pattern with context-aware adaptive components.



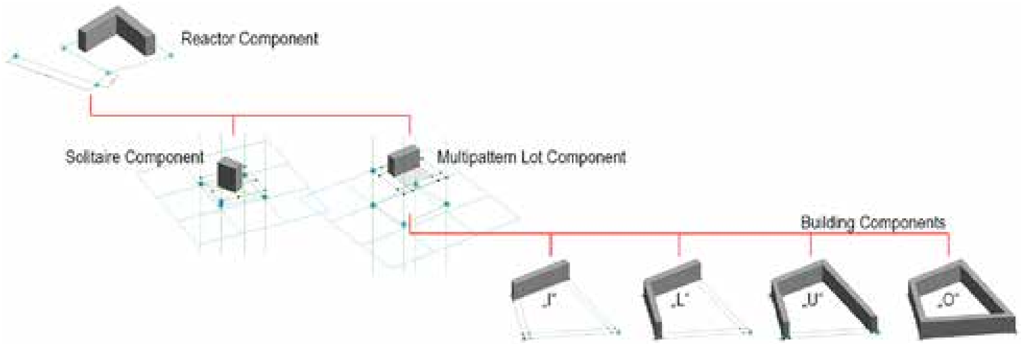


Figure 3
Nested component structure.

COMPONENT OVERVIEW

For the purpose of surpassing a mere proof-of-concept stage, component types were developed for most commonly found building shapes: I-shaped, L-shaped, U-shaped, O-shaped and solitaire. The lot and building block components are organized in a nested object structure (Figure 3). The lot component, a pattern-based element, is intended for:

1. Placement on and distribution across the city block's grid.
2. User input. Depending on the component design, the input can consist of different types of rules and constraints such as building dimensions, setback, plot area ratio (PAR), floor-to-floor height, usage type, building orientation etc.
3. Evaluation of lot geometry (dimensions and angles, where applicable).
4. Communication of user input and lot geometry to the nested building block component.
5. Calculation of the required numerical data needed for design evaluation (e.g. building footprint, building volume, cubic index etc.).

Nested inside the lot component are one or several instances of building block components. These adaptive components are linked to their parent component by parametric relationships. As they are created as what is referred to in Revit as "non-shared" components, they are completely absorbed by their parent component and can neither be selected nor scheduled as separate elements in the project environment. They mainly consist of "dumb" geometry and only perform the following tasks:

1. Evaluation of the input received from the parent component.
2. Generation and positioning of building geometry in the context of the lot geometry based on the received inputs.

In the case of more complex design intent such as gradually increasing the building density towards a subregion within the planning area, lot components can be nested in another context-aware adaptive component that is able to track its proximity to said subregion and drive these parametric constraints in the building block components, as described by Dieckmann and Kron (2012) for curtain wall panels.

Lot Component Anatomy

The lot component is created as a pattern-based element, a component that is based on a number of placement points. As the lot component has to adapt to varying geometric conditions set by the geometry of the city blocks, it needs to be aware of its own shape and size, i.e. the lengths of its edges and the angles between those edges. In Revit, such properties can be measured by using so-called reporting parameters that report the varying dimensions for each placed instance of a pattern-based component. While the components may be placed on sloped surfaces, the dimensions need to be measured in top projection in order to be used for the calculation of areas and lengths later on (Figure

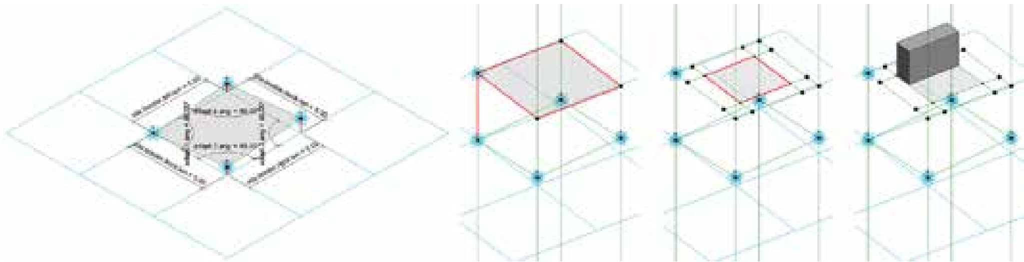


Figure 4
From left to right: a) Dimension measurements on horizontal plane, b) Horizontal datum between vertical rays, c) Definition of building zone, d) Placement of building component.

4a). This is done by hosting all the dimensions on the horizontal work plane of the first placement point.

The geometry of a pattern-based component by default inherits the orientation of its host, i.e. the divided surface of the city block. That means that vertical elements created in the lot component would rather orient themselves according to the surface normals of the city block than vertically at their point of placement. By changing the orientation mode of the placement points the lot component geometry can however be forced into a strictly vertical orientation. The placement point location can then be projected upwards by means of vertical rays. On sloped lots, the building may have to be moved up or down so as not to be fully or partly immersed in the terrain. This can be achieved by creating a horizontal datum between the aforementioned rays (Figure 4b) that can be moved by manipulating a parameter that controls the vertical offset of the datum.

The horizontal datum serves as the placement plane for the building component itself. It is subdivided into nine zones by projecting the street offset for all four sides of the lot onto the datum (Figure 4c). These offsets can be controlled by the user through four parameters. In case the street offsets of opposing sides of the lot overlap, the user inputs will be substituted by a "safe" value that is automatically calculated.

The four intersection points of the street offsets form the location for the placement points of the building component (Figure 4d) and also mark the vertices of the central zone that forms the basis for the building footprint calculations (see below). Once a building component is placed here, its type can be controlled by a parameter, making it easy to change the orientation of the component (front, right, back and left side of the lot) as well as the building shape (I, L, U, O). This also allows for the subsequent creation and substitution of other building shapes essentially making it a modular system. Additionally, all the parameters that control the building shape (building depth for all sides of the lot and building height) are also passed to the subcomponent. As stated above, the building subcomponents merely consist of the building geometry driven by the lot component parameters and thus warrant no further description.

For the purpose of calculating the building footprint and related data like floor space and building volume, the central zone is again subdivided into nine zones, this time by using the building depths for the four sides. Again, the depth for each side is user-controlled with a safeguard against overlaps as described above for the street offsets. The footprint of each building type can now be calculated as the sum of some of the zone areas (Figure 5), depending on the selected building type, e.g. the footprint of the O-shaped building would be the sum of all zones except for the central zone. The zone areas themselves are calculated on the basis of the reporting parameters (see above) using Heron's formula and the law of cosines. Subsequently, all other data necessary for evaluation such as cubic index, floor area ratio or site occupancy index can be derived from the building footprint, the number of floors, the floor height and the site area. In Revit, custom component parameters can not be scheduled or annotated in the project environment by default.

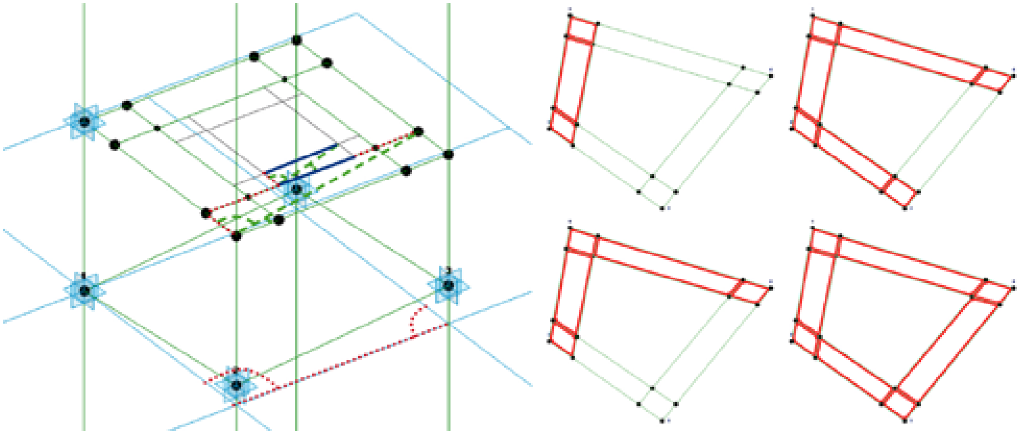


Figure 5
From left to right: a) Known (red, dotted), auxiliary (green, dashed) and calculated (blue, continuous) dimensions for area calculations, b) Zone combinations for area calculations.

Thus, in order to have the data readily available in the project for evaluation, they need to be declared as so-called "shared" parameters making them available globally (in the component itself as well as in the project).

Component Variations

The lot component can be used as a template to create further variations. They can either be different building types than the four types described above, more complex parametric components that utilize the lot component as a subcomponent or a combination of both.

The solitaire component (Figure 6a), for instance, makes use of the spatial and parametric framework of the lot component. However, it needs neither the street offset grid nor the majority of parametric relationships that aid with the area calculations for the standard building types (I, L, U, O). Instead, it contains a center point for the free-standing building geometry that can be moved parametrically in U and V direction on the lot surface. The building geometry that is hosted on the point in turn has a rotation parameter to allow for flexible alignment of the building mass.

A reactor component (Figure 6b) as described above can use either the solitaire component or the standard lot component as nested subcomponent. It is basically an adaptive component that sets up rules for the behaviour of its subcomponent. It has one or several additional placement points that act as sensing devices. By hosting these additional placement points on certain fixed points in the project and measuring their distance from each placed

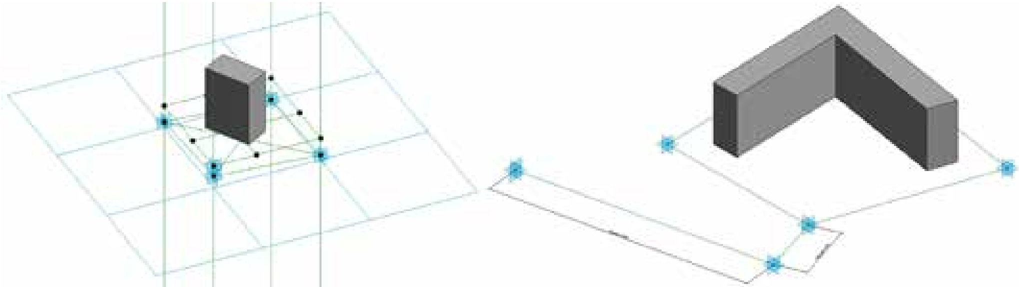


Figure 6
From left to right: a) Solitaire component, b) Reactor component.

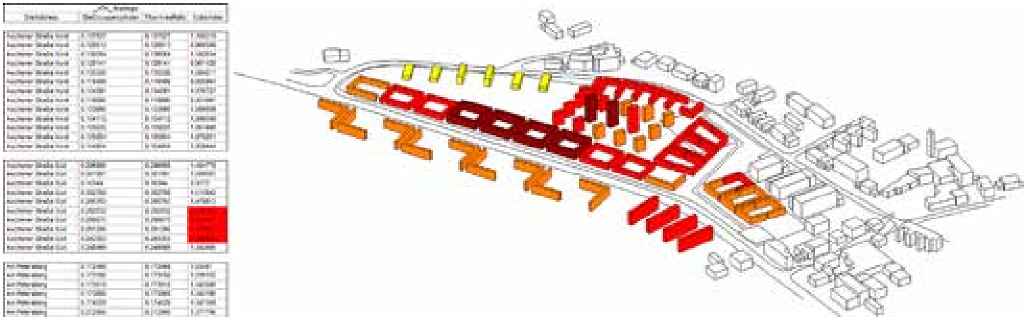


Figure 7
From left to right: a) Example of a lot schedule with conditional formatting, b) Example of a filtered model view colour-coded by cubic index value ranges.

instance of the reactor component, the components gain spatial awareness. This information can then be used to control the geometric properties of each placed subcomponent, e.g. the number of storeys.

WORKING WITH THE TOOLKIT

The typical workflow has been, at least in part, described above already: The city blocks are created as mass surfaces and subsequently subdivided into lots. Depending on design intent, several distribution methods (uniform, uniform with exceptions, patterned and reactive/parametric) are available (Figure 1). The component type(s) assigned to a block, a lot or a pattern can be changed and their instance properties can be modified. The shapes of the mass surfaces themselves and the number of their respective subdivisions can also be modified at any time. Moreover, several out-of-the-box functionalities like design options (managing different design alternatives) and phasing (managing the temporal properties of elements, i.e. differentiating between existing and new building blocks) can be utilized to structure and control the design.

The main reason for using a BIM environment for urban design, however, is the ability to create information-rich content and leverage that information to evaluate the design. All the numerical data produced by the placed components can be easily scheduled. Each lot component contains a flag parameter that facilitates the creation of a schedule that only displays the lot components placed in the project and ignores all other site components available in the model. The schedules can utilize conditional formatting to highlight lots that do not meet certain requirements like, for instance, a cubic index that exceeds a certain limit (Figure 7a).

A schedule is, however, just one way of looking at information. The same information can also be visualized in isometric, perspective or plan views, displaying the information in a spatial context. In Revit, model views can be reformatted with so-called view filters. By means of a few view filters a perspective view of the project can be colour-coded according to value ranges of any given parameter like, for instance, the cubic index of each lot, with different colours for different value ranges (Figure 7b).

Often, the building type has a significant influence on the measurable characteristics of a building. For instance, the energy use of a building depends quite heavily on the activity within that building. There are some statistical resources available for that kind of information, like the Buildings Energy Data Book by the U.S. Department of Energy [6]. However, for the purpose of this paper, the authors have focussed on costing. In a lot of countries, there are statistical data available on the building costs for various building types. For the german market, this data is made available by the BKI Baukosteninformationszentrum (2013). In Revit, external data can be inserted in the form of so-called key schedules, either by inputting it manually or by using third-party applications [7] to import it from Excel. A row of values from a key schedule can be assigned to a placed component by means of a key parameter.

After that, a costing schedule can easily be created that contains parameters that, for instance, calculate the building cost on the basis of the building volume and the cost per cubic meter specified in the key schedule for a particular building type.

Once the schedules and filtered views have been set up properly, the project file can be used to create a project template for future urban planning projects. This way, the information will be readily available as soon as the designers start placing the first lot components – they could even model the project in a filtered view for direct visual feedback.

DISCUSSION

The presented method facilitates a quick, albeit makeshift, workflow to create early design models for large-scale urban planning projects in a BIM application. All relevant numerical data is generated on-the-fly by the components themselves as they are placed in the context of the site. The design can therefore be immediately evaluated – either numerically or graphically – making it easy to explore different design alternatives. Additionally, the chosen host application has the capability of performing environmental analyses for the impact of sun and wind on the design. The components, of course, still have some limitations, e.g. a useful functionality would be to be able to assign more than one usage type to a building, perhaps per storey.

For the sake of interoperability, a sensible next step would be to reach the capability to export the model to CityGML format. Previous research on the subject of marrying IFC and CityGML quoted in this paper has focussed on the conversion of entire building models to several levels of details (LOD) in CityGML. In this specific case, a conversion of single elements (generic models) in the building model to LOD 1 or 2 CityGML building entities would do the trick.

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[Architectural] Reasoning over BIM/CAD Database

How to combine reasoning powered ontologies with BIM/CAD tools (and vice-versa?)

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Abstract. *Design activity is pervasive as it is increasingly expanding into all sectors and every day it is increasingly difficult to anticipate the often unpredictable changes resulting from new inventions and changes in technology, tools, methods and social customs using current design systems, and at the same time we need to preserve and store knowledge and experiences that can help facing aforementioned problems. The present paper illustrates an innovative Rule Layer overlying existing commercial software in order to model Reasoning and Performance verification Rules to be applied to design instances. The authors developed two different prototypes, one on BIM and one on CAD commercial software in order to validate the proposed approach. Results demonstrate the general system potentials opened up to further research development and deepening.*
Keywords. *Building ontologies; building design reasoning; BIM/CAD; collaborative design.*

INTERLEAVED WORLD

Comparing our "era" with the past, people in developed countries obviously live in better conditions than before due to the organization of society and technological evolution. On the other hand, sociality has been replaced by competitiveness, mainly as a result of increasing complexity and changing needs that require new approaches in all human activities in order to meet increasing demands (Einstein 2006).

The problems are mainly related to the 'idea' of science and science law we have. In the past, our general conceptual elaborations were based on Thirties period. That time all academic institutions in the world completely absorbed what was elaborated from most advanced scientific and philosophy researches: the importance of science (also social) facts, of measurable quantities, referred to phenomena expressed in mathematical-analytical formulas.

Hence fundamental science courses were taught, on which 'objective' base the following disciplines were set up. This 'functional' logic characterized scientific as well as humanistic Schools.

In short: avant-gardes inquired into "first" principles until the First World War; afterwards, the results of these researches were applied to well limited scopes. It was usual to describe phenomena by means of first order theories (superposition of effects) in application domains precisely defined (limit conditions).

However, in the middle of last century new studies and ever-growing specializations have led scientific communities to verify that many phenomena could not be explained by means of these two assumptions. We discovered that also apparently simple phenomena are interrelated with context so belong to the category of Complexity, the right approach to these studies is a multi- and cross-disciplinary ones and very often only Chaos theory can explain them. We passed from mathematical formulae expressed by means of multiplications and logarithms to system of integrals with not exact solution, but partial derivative differential equation solutions; lastly concepts can be computed thanks to performative computer systems.

Referring to Building Design Tools, the evolution from paper and pencil to CAD systems, to Object Oriented Systems and ultimately to BIM platforms has led, step by step, to new design methodology and consequently to different design results. As a matter of facts, these methodologies and tools together with new social and architectural sensibilities influenced and in turn were influenced by current contemporary buildings and also by high performing ones as shown in architectural masterpieces of archistars like Eisenman, Gehry, Toyo Ito, Fuksas, etc.

CAD systems and their three-orthogonal coordinates systems have certainly supported the design process in building representation but have also indirectly influenced generations of architects and designers as far as space configuration and overall building design are concerned. These systems were used to represent only geometry, 2D or 3D and sometimes tagged entities to specify space destination or specific entity meaning.

Object-oriented Systems and actual BIM platforms allowed another step to be taken towards Design and Process Support Tools: each represented entity has a recognizable tag linking it to a general concept and a set of properties that contribute to meaningfully defining the designed building component, space, 4D and 5D design process.

In the contemporary world, which is increasingly linked to reduced distances in terms of space, language and, sometimes, even culture, humans are evolving (or counter-evolving) into users connected by emails, social networks, news and any other web-based sources.

All these social links among different users contrast with the exponential increase in specialization of professionals in their own domain: as stated by Simon: “Once a profession reaches the point where it takes 10 years to master, it tends to break up into specializations”.

In Architectural Design processes, many different specialist domains are involved as well as several specialist designers in their respective fields. These are changing the twentieth century-related design approaches made up of functionality verification, client requirement checking, cost control and time scheduling, cross disciplinary expertise into increasingly narrow specializations and knowledge sectoralisation, under the effect of increasing technology complexity and discipline multiplication.

Nowadays buildings are evolving into “smart” buildings, control panels substitute light switches, sensors will ultimately allow program building services to adjust performance to suit changing environmental conditions, forms will change according to weather, climate or use functions.

However, resources are limited, costs are out of control in a blurred economic, technical and social context, and sustainability becomes a necessity, not just a possibility.

In order to allow different Specialists to collaborate in a Design Process in an effective and productive way, the present abstract presents a prototype structure for an innovative design tool, a *System* that adds a Reasoning and Performance Layer to existing BIM and CAD software.

BUILDING DESIGN SUPPORT TOOL

Existing BIM software systems are evolving into Collaborative BIM environments: different domains are combined into a single software or several connected software families; user interfaces are changing into domain-oriented GUIs that adapt to suit the target user.

The actual design activity is increasingly being extended into all sectors and every day it is more and more difficult to try and foresee the often unpredictable changes resulting from new inventions and changes in technology, tools, methods and social customs using existing design support tools.

In addition, client needs, requirements and constraints are becoming more specific day by day (for instance, real estate societies) and designers have to continuously check out their own design solutions in order to fulfill certain domain expectations.

Each Specialist Designer with her/his own expertise uses 'personal reasoning rules' in order to develop her/his own design solution.

In order to verify specialist domain constraints and general overall design consistency, coherence and congruence, "on-the-fly" performance verification systems are needed.

The proposed Layer is complementary to existing BIM and CAD software in order to support on-the-fly designers, allowing them to model their respective constraints, verification algorithms and checking rules at different levels (Beetz et al. 2006; Fioravanti et al., 2012):

- Internal Domain Private Rule Verification: Actors model their own rules in order to check the on-going design solution in their own personal specialist domain;
- Internal Domain Shared Rule Verification: Actors check rules shared by other actors involved their own private design solution in order to check for possible conflicts with a different specialist domains;
- Collaborative Rule Verification: in the Shared Design Workspace (Loffreda and Fioravanti, 2009) performance/verification and checking rules shared by all the actors involved in the specific design process are performed in order to evaluate and check out the proposed design solution (with input needs and requirements).

PROPOSED SYSTEM STRUCTURE: A MIXED MODEL

Referring to previous research results (Fioravanti et al., 2011a; 2011b) the proposed Design Support Tool combines existing software tools with a system composed of developed routines and Knowledge Structures. The research analyzed and tested several software(s), although the proposed system uses the following components:

- Autodesk Revit 2013: BIM software for Private and Shared Design Workspace Interface;
- Protégé OWL 3.4.8 (Frames): Ontology Editor for Knowledge Modelling in terms of Hierarchy, Properties and Entity Relationships;
- Semantic Web Rules Language Plug-in: Protégé plug-in for Rule Modelling on Ontology Entity Representation based on predicate logic formalization;
- Jess Rules: an ontology reasoner for rule checking and verification [1];
- Revit DB: a tool for Revit projects exported into a Database;
- Oracle MySQL: a relational database management system.

In order to validate the proposed research, authors developed ad hoc plug-ins, software add-ons and tools to connect Knowledge Structures implemented in OWL with Autodesk commercial software.

This link with CAD software expresses proposed platform potentials and also opens up fresh discussion on future developments:

- Link with existing commercial software with its limits and constraints due to its proprietary nature;
- Enterprise system development including "ad-hoc" and/or open-source graphical representation systems.

Reasoning results could affect the geometrical aspects of the modeled entities, but due to the "proprietary" nature of Autodesk Revit 2013, it is not possible to interact with geometrical properties on built-in Families from external software, not even from the Database via the Revit DB Link.

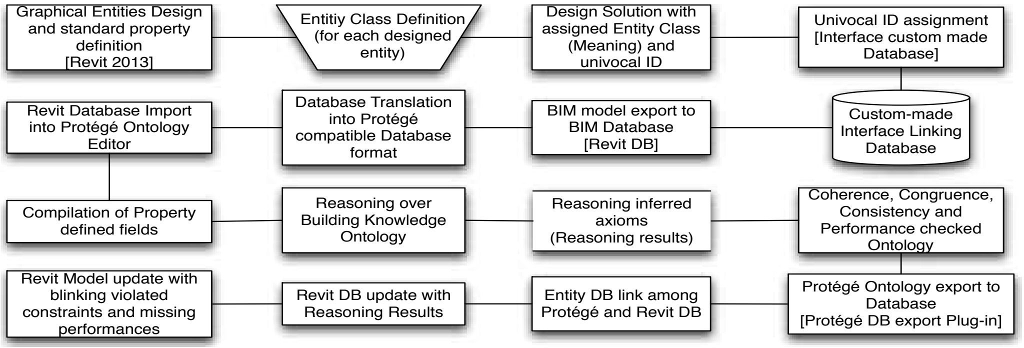


Figure 1
Design process Flowchart.

PROPOSED SYSTEM IMPLEMENTATION WITH BIM

Phase 1: Knowledge and Rule Modeling

In order to represent Building Knowledge Entities, a specific Design Ontology has been developed. It has been structured with reference to a Meanings-Properties-Rules Template devised by the authors and implemented by means of a Protégé Ontology Editor.

Entities description, properties, relationships and hierarchical structure have been modeled by means of predicate logics (Hofstadter, 1979) and ontology formalization [2]; the Knowledge Representation allows queries and constraint verification by means of specific reasoner and rules formalization in Semantic Web Rules Language (SWRL).

In order to interrogate Design Solutions, Ontology Rules have been implemented and tested on prototype instances of developed Ontology Classes: a hospital ward has been modeled both in terms of general entity Classes and testing instances (spaces and components) (Calvanese et al., 2008); moreover SWRL rules have been formalized to check specialist domain constraints:

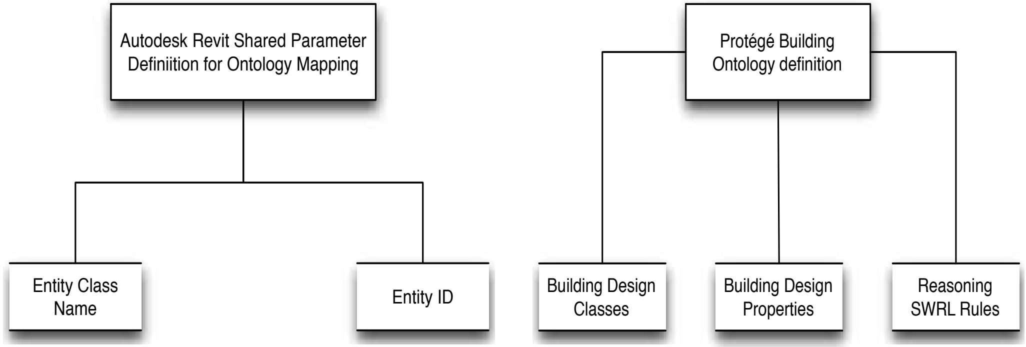
- Space configuration and topological relationships among spaces;
- Furniture and equipment provided for each building unit;
- MEP system, Structural elements and Space configuration compatibility.

Phase 2: Building Design Process workflow

The proposed prototype concept has been conceived of as a sequence of necessary steps (Figure 1) that are transparent to final users (designers).

1. Actors develop their own design solution by means of Autodesk Revit 2013;
2. Specific Revit shared parameters have been defined in order to specify Ontology Class and IDs for each designed Revit entity (Figure 2);
3. BIM Design Solutions include only BIM entities and properties; that implies: no space semantic definitions, no specialist domain properties, no rules;
4. BIM model is exported to a Database by means of Revit DBLink;
5. An open-source database MySQL is created in order to interrogate the exported database;
6. An ad hocLinking Database has been created in order to connect exported Revit DB (Revit data) and Protégé Ontology Instances (Knowledge Entities);
7. Respecting Protégé Database exporting format, Knowledge entities are instantiated and property fields filled in with available values from Revit designed entities;
8. The DB obtained represents a combination of Knowledge and Graphical Entities in an Ontology query-able format;
9. By means of modelled SWRL rules, constraints, performance, consistency, coherence and congruence verification can be performed;

Figure 2
Autodesk Revit 2013 and Protégé Frames 3.4.8 customization.



10. SWRL inferred axioms can be checked and verified by each Specialist Designer;
11. By means of Protégé "Export to Database" command, an inferred Entity Database is created;
12. The Revit Database is then updated with new values and definition from the inferred Entity Protégé Database by means of the developed Linking Database.

Due to the proprietary nature of Autodesk Revit, even if Reasoning Rules in Protégé may possibly affect geometrical properties modifying and/or adding values, Revit does not allow them to be changed because they are System Parameters and it is not possible to edit them out of Revit itself.

Due to this limitation, in order to validate the proposed system, the authors implemented plug-ins and add-ons for AutoCAD® which allows interaction with the DXF drawing format.

PROPOSED SYSTEM IMPLEMENTATION WITH CAD

Phase 1: Knowledge and Rules Modeling

Knowledge Ontology modeled by means of Protégé for the above-mentioned test has been modified in order to allow further prototype tests on the proposed system.

AreaXY property has been linked to Product class and its sub-classes and several has_xn (with n from 1 to 8) have been linked to classes in order to specify 2D geometrical instance definition.

The CAD prototype refers to AutoCAD® for graphical representation and is limited to lines and 8-vertex polylines representation to suit the modeled knowledge structure.

Phase 2: Building Design Process workflow

The following workflow shows the step-by-step implemented prototype:

1. Launch Protégé Ontology Editor with classes, properties and rules definition;
2. Query Tab launch: classes list (Figure 3);
3. Class List Export in a TXT file;
4. Autodesk AutoCad Launch;
5. AutoLisp implemented application launch for automatic Layer creation with layer name equivalent to class name (Figure 4);
6. Design solution representation by means of 2D lines and/or (at most) 8 vertex polylines;
7. Design solution saved as DXF format file;
8. A specific software has been implemented in order to parse the saved DXF file and then to create as many CSV files as the layers used. Each CSV file will contain as many rows as elements are present in corresponding layer in DXF file, separating the element features with a semicolon, for example sake:
   - Instance type: Line or LwPolyline;
   - Handle: unique AutoCAD® ID;
   - numVertex: number of instance vertex (only for polyline definition)
   - has_xn-has_yn: (with n from 1 to 8) x and

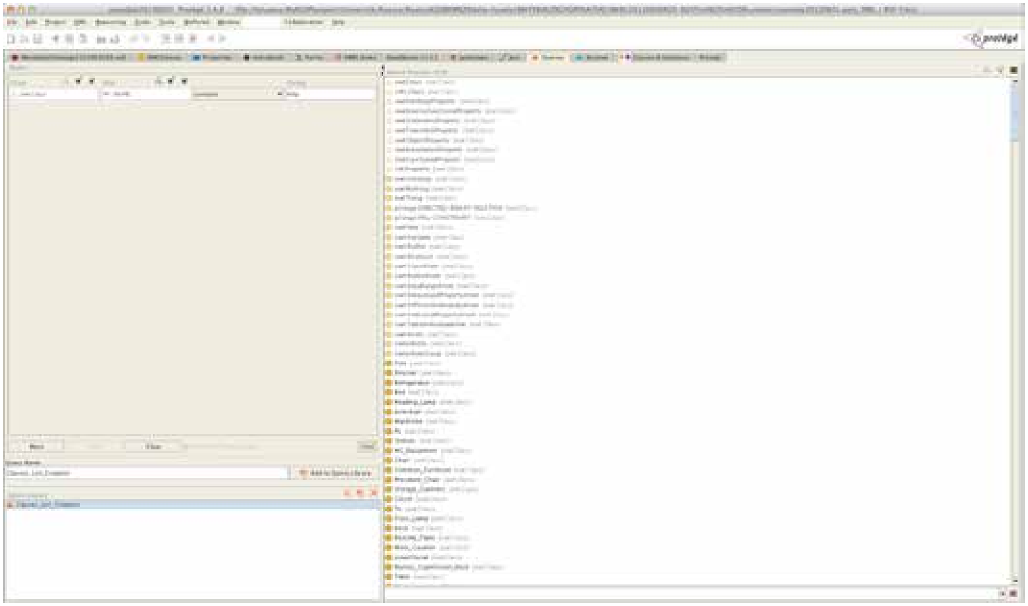


Figure 3
Protégé OWL 3.4.8 Ontology Editor. Query Tab Class List result.

y vertex coordinates;

9. In order to facilitate DB content management, the CSV files obtained are merged into a single Microsoft Access® DB, importing each CSV into a different table of the database;
10. ODBC DNS system link with the created DB;
11. Protégé and DataMaster v.1.3.2 Launch: allows the linked DB to be connected and the existing tables can then be imported into the existing ontology;
12. By setting Datamaster import under Thing, the system will automatically create as many instances as there are rows on each table as a subclass of related Class with name equal to the table name. As a result of the previous steps, the table name will correspond to the ontology class name so that instances will inherit knowledge properties and rules definition including also geometrical values obtained by AutoCAD® representation;
13. A testing Design Rule was implemented by means of SWRL in order to validate proposed system potentials. The testing rule checks all the Room instances and verifies whether the bounding windows area is greater than room area/8 (Figure 5);
14. Reasoning rules are applied by means of the Jess Rules [1] reasoner and, according to rules definition, unverified instances will have the Boolean modified property set to true.
15. Query Tab launch: at this stage it is possible to search for all instances with modified Boolean property set to true;
16. It is then possible to export the modified Instances List as a txt file with handle property associated values;
17. By means of some other developed software, the system will check the previous created DXF file, compare it with exported txt file and modify the entities colors to Red if the handle in dxf is present also in the exported txt modified entities list.

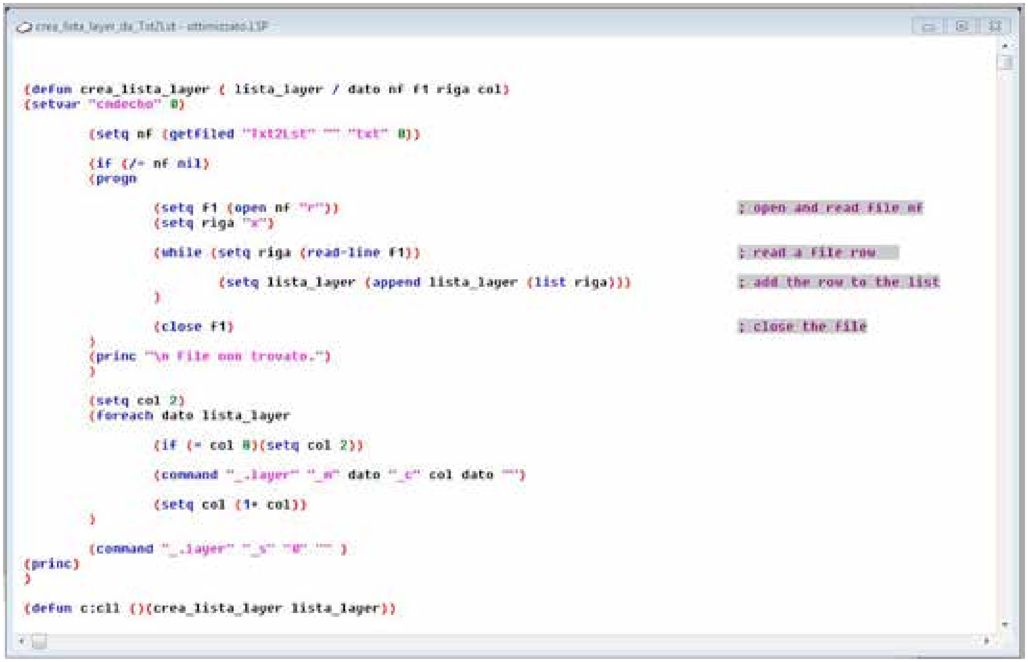


Figure 4
Autodesk Visual LISP Editor. Autodesk AutoCad Layer creation program.

CONCLUSIONS

The system prototype illustrates an innovative approach to Building Design Support Tools by means of a mixed model using commercial application programs, ontology management systems and custom-made reasoning rules, database and interface tools.

A set of existing BIM software, Knowledge Representation systems and Database improves existing commercial software, enhancing definition and the modeling of building design.

In order to develop an innovative, powerful, scalable and useful design support system, the authors implemented an ad-hoc Linking Database interfacing previous modeled Design Knowledge Structures (ontology classes and properties) (Fioravanti et al., 2011) with Revit Entity Database. Afterwards SWRL Rules can allow the combined (Knowledge and Graphic) Database Ontology to be queried in order to perform consistency, coherence, congruence and performance verification on design solutions.

Due to the proprietary nature of Revit®, first prototype implementation did not allow the Revit designed entity to be modified even though the authors used specific Revit add-ons and extensions. According to these limitations and in order to validate theories and design process logic, the authors developed a second prototype based on CAD software.

This approach allowed a different design process workflow definition; plug-ins identification and specific program implementation help check constraints and design reasoning rule results affecting 2D CAD developed design solutions and demonstrating the overall system potentials.

Tests showed that it is possible to enhance existing commercial software by applying on top of them a Reasoning Layer which includes Specialist and/or Common Rules, expertise and Building Performance verification.

Each involved Actor will then be able to model

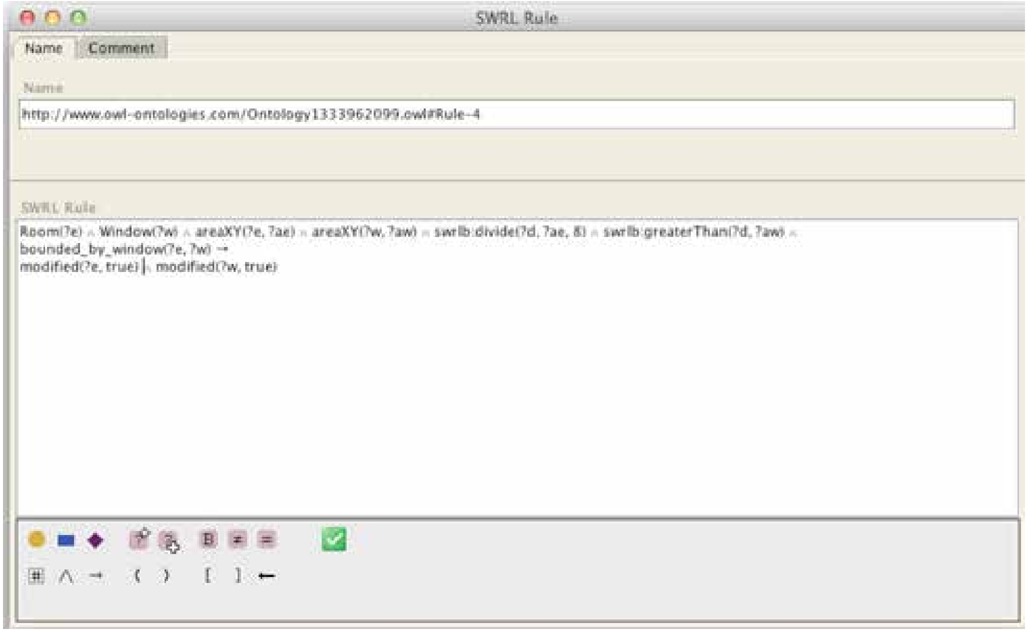


Figure 5
Protégé OWL 3.4.8 Ontology Editor. SWRL Testing Rule definition.

as many rules as needed in the specific "on-the-fly" design process checking:

- Personal Specialist Domain consistency and internal coherence;
- Other Domain Rules congruence;
- Overall Design Verification and Client Needs fulfillment.

This system represents an on-the-fly tool for Specialist Designers designed to suit Client needs and to correct the on-going design process according to performance and requirements goals.

The implementation of the system shows its potentiality in proposing a new generation of Design Tools that allows further research development and deepening.

As far as its scalability is concerned, the proposed tool is easily applicable to other Knowledge "Realms" aimed at improving different Design and Collaborative Processes in order to enhance knowledge sharing, innovation spreading and collaborative problem solving.

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Experiencing BIM Collaboration in Education

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Abstract. *In a context of a slow uptake of the Building Information Modeling (BIM) methodology in the Flemish region, we present the results of an educational research project, carried out over 4 semesters, in a multi-disciplinary, cross-campus collaboration. This project fosters an improved application of BIM, information management and communication, by organizing building teams involving students from different schools. The project partners collaborated on a shared framework of supportive learning material, collaboration scenarios between teams of students and the integration of digital tools for communication, information management and collaboration in the curriculum.*
This article, in particular, will elaborate on one of the collaborative exercises, involving architecture and engineering students, using BIM for modeling, information exchange and model evaluation.
Keywords. *BIM; education; collaboration; interoperability; IFC.*

INTRODUCTION AND CONTEXT

While the use of the *Building Information Modeling* (BIM) methodology is increasing worldwide, we notice a slow uptake in the Flemish region (Belgium). In contrast with surrounding countries, such as The Netherlands or the UK, there is no governmental incentive that promotes the use of BIM for building projects. We are far from the adoption rate as noted in the *McGraw-Gill SmartMarket* reports (Young Jr. et al., 2009; Bernstein and Jones, 2012), which mostly reflect the North-American industry BIM uptake. Eastman et al. (2011, chap.4) describe the value of BIM for building owners, but apart from a single initiative, the demand for BIM from building owners in our region is non-existing. Even architects, who are using BIM software more often, apply it only in their own, local context and still rely on traditional, drawing based collaboration with other building partners. Local software vendors seem to claim no more than 20 or 30% of their clients have licensed BIM software, while the effective use in projects is probably even lower. While the BIM concept is slowly gaining more attention, amongst professionals and educators, it is sometimes regarded as merely a software tool or an alternative method to make 3D models.

Too often, its usefulness is misunderstood, as it is not seen as part of the design process. As such, the added value and the potential productivity gains that are promised by BIM use are not experienced and might hinder BIM adoption. This is in line with the experiences mentioned by Holzer (2012): the resistance to process changes and the "*monodisciplinarity*" of BIM tools. Hartmann and Fischer (2008) note the lack of knowledgeable practitioners as one of the major bottlenecks for widespread BIM adoption. Lockley mentioned in the *NBS Building Information Report* (Anon, 2011, p.20+21) the important role for educational institutes in the unavoidable transition to BIM. Livingston (2008) argues that BIM manifests itself both as a 3D-modeling tool (the software) and an information management system, which aids students for "a greater understanding of building systems integration".

The authors of this article participate in the *COM.BI project*: "*Communication and management of digital building information in a multidisciplinary team during the construction process*" [1]. This two-year educational research project implements collaboration in building teams and introduces innovative software tools. Since all building-related disciplines are represented within the *KU Leuven Association* [2], there is an opportunity to form multi-disciplinary student teams and to share knowledge. Also the tutors can share their different fields of research and professional experience. The didactical approaches and methods have been elaborated in (Boeykens et al., 2013), whereas this article will focus on how the BIM methods and technologies are being applied in an educational context.

We deliberately want to foster the application of the BIM methodology in the architecture and engineering curriculum, by allowing students to experience the benefits of using BIM in a collaborative context, rather than as a mere modeling and documentation tool, as it happened before. Students will learn to work together, to exchange information using BIM models and to apply BIM as part of the design process. We want them to migrate from "*little*" BIM to "*BIG*" BIM (Jernigan, 2008), which includes model exchange and model evaluation.

CHALLENGES

The first challenge is mostly a mentality problem. As witnessed by the authors, the majority of architectural design studio work still relies on traditional drawing based methods, where 2D CAD software, such as *AutoCAD* and *VectorWorks*, is used mostly for representational purposes or construction documentation. Ambrose (2012) discusses some of the pitfalls and how BIM could be applied in a design studio context. He mentions an underestimating of the way digital tools and methods change the "*way we make* architecture". By defining BIM as a design methodology instead of a design tool, it "acts as *provocateur* to design education and the *how* and *what* of the academic design studio". Many designers see BIM as a hindrance to the creativity during the design process. Morton (2012) expresses this concern in schools, where teachers often fail to see beyond the tool and how BIM can be "interfaced" with the design process. Even students who are being introduced to BIM, often fail to look beyond the 3D modeling aspects as mentioned by Weber and Hedges (2008). In that context, prior CAD knowledge proved both beneficial and discouraging at the same time. Beneficial, since drawing functionality is still provided to finish the drawings where the model is incomplete or lacks detail; discouraging because drawing a floor plan directly is usually quicker in 2D. "The simplest tasks proved to be a challenge." Students and design studio teachers need to look beyond the effort inherent with BIM.

To avoid too much friction of introducing a BIM-based working method and enforcing it in the design studio, the project collaboration was taken out of the design studio assignment and hosted as part of a course where the authors were directly involved. There is the *Architectural Computing* course on the side of the architectural-engineering Bachelor program, during the fourth semester and the course on *3D-Design* on the side of the construction engineering students, which is an elective in the Master track. However, this directly implies a second challenge, as students with different maturity levels will need to work together. They have different background knowledge, do not possess the same technical expertise and speak a partially different language.

There are also multiple technical challenges. It was decided for this exercise to enforce the usage of BIM software and to apply it intensively as part of the collaboration. The different BIM applications that are used in the two schools are inherently incompatible, as they apply a proprietary data model and file format. In the architecture course, *Graphisoft ArchiCAD* was used, whereas the engineering course relied on *Autodesk Revit*. It was a deliberate choice not to avoid this challenge, as it is a good illustration of a real context of various players and tools. Even if everyone would use the same software, interoperability is not guaranteed. Version differences can make file exchange impossible: e.g. it is not possible to export Revit models to older releases. In addition, even when people would use the same software version, there are still many differences in model structure or applied model templates.

The evident solution was to rely on *ISO/ PAS 16739 IFC* (*Industry Foundation Classes*) [3] to exchange building models between ArchiCAD and Revit. However, 100% complete information transfer cannot reasonably be expected due to implementation limitations. Rather than to complain about this, we decided that this represents a realistic context for collaboration, so the challenge was included as part of the exercise. This was motivated by the obtained successes in several case studies and reports (Bos, 2012; Mitchell et al., 2007; Hitchcock and Wong, 2011), which testified of the usability of IFC and how it can be implemented in construction projects, despite most authors acknowledging that the information transfer was seldom perfect. As long as project team members have means to assess the limitations and are willing to communicate constructively, this should not prevent collaboration. Moreover, deeper understanding of the usage of IFC in practical scenarios can help software developers to improve their BIM implementations.

In addition, there were several logistic challenges. Students had different timetables and were located in different cities, about 90 km apart. Moreover, the architectural students were more than 100, whereas the engineering students are part of an elective course, for which only six students registered this semester. Only some of the groups with architecture students could be linked to an engineering student. The assignments for all groups, however, had to be similar and present equal work.

METHODOLOGY AND ORGANIZATION OF PROJECT TEAMS

Since design collaboration is an important driver for BIM adoption, we will focus on the collaborative aspects of BIM, by simulating a *Project Team*, containing different roles and disciplines, with students. Because it was not feasible to assign an external engineer to each project team, we had to make the distinction between internal, local collaboration (e.g. architects from the same office) and collaboration with an external office. The two types of collaboration provided a challenge of trying to balance the amount of work, as not to place an advantage on one or the other.

Figure 1 gives a schematic overview of the collaborations. We indicate different roles, the used software systems and document types and the information flow.

As can be seen on the previous diagram, in the collaboration with an external engineer, the architectural team collaborates internally on the design model (e.g. using *ArchiCAD TeamWork* [4]), whereas the engineering student fulfilled a consultant role, focusing on heat-loss calculation and designing the ventilation system. In the internal collaboration, there is an additional role indicated, namely that of the model evaluator. It was decided to have the project team assign one group member with this role, as an equivalent consultant role. These students perform some qualitative and quantitative analyses of the design model, using model evaluation software (*Solibri Model Checker* [5]). This necessitates the usage of IFC as an exchange format.

PROCESS AND WORKFLOW ORGANIZATION

The design team prepares an architectural model that is transferred to the other disciplines, to provide feedback on how to improve building performance. To support this process, students are provided with basic guidelines and learning material, but they have to organize the actual collaboration independently, by specifying tasks and appointing responsi-

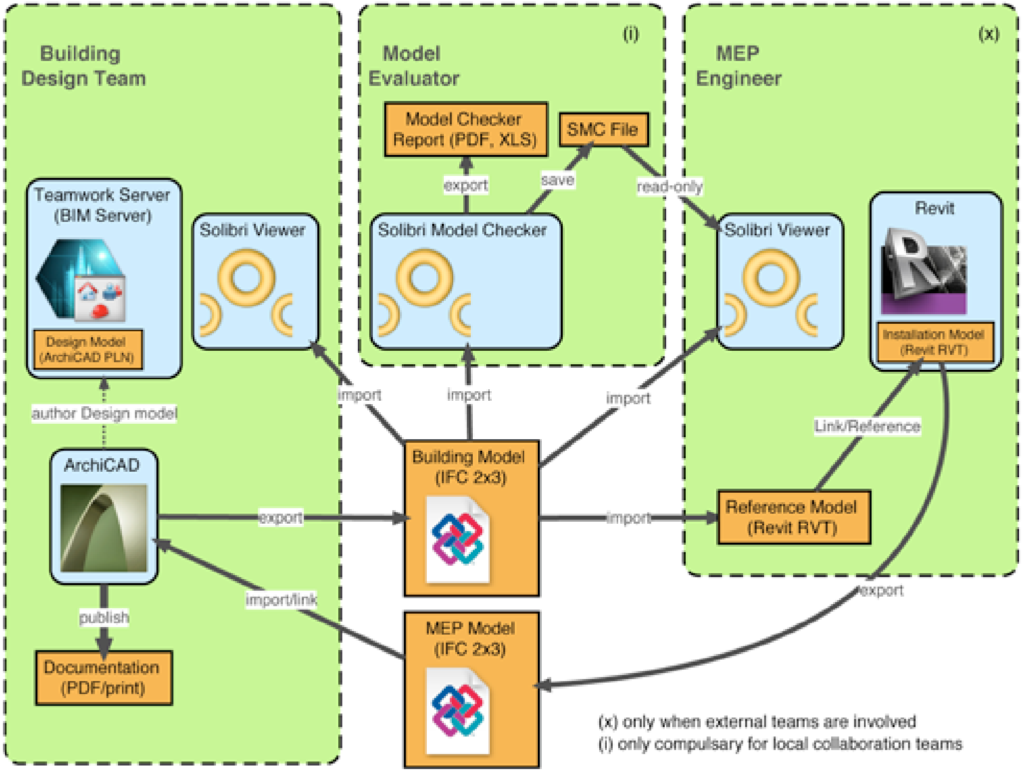

Figure 1
Schematic overview of the collaboration.

bilities. The guidelines document is derived from a regional, localized *IPDP* (*Integrated Project Delivery Protocol*) document [6], in which the students need to formulate the different roles in their team, responsibilities, the information flow and the necessary collaboration activities (deadlines and meetings). We reformulated this document, which was oriented to professional practices, for an educational context, but kept a similar objective. Instead of formulating the document as a static checklist, it was written as a series of open questions, for which the students needed to define an answer within their group.

buildingSMART [7], an organization focusing on interoperability and building process improvements, defines *Exchange Requirements* (*ER*) and *Model View Definitions* (*MVD*). To prepare the collaboration between design team and external consultant, the engineering students set up ER, including room areas, volumes or the façade area. This enforces them to specify required information precisely and unambiguously, including the correct way to measure certain quantities, e.g. gross or net values and inner or outer dimensions. Based on the ER, the architectural model is filtered to contain only the requested information, rather than transferring a full model. This is in line with the MVD concept. Before the filtered model is exported to IFC, it can be further optimized to improve model exchange, as will be described in the next section.

To accompany the exported model with quantitative results, the architects create additional table schedules. Engineering students who receive the

IFC model follow a *reference model*-based approach, indicating that they will use the exported models for information exchange only and continue working in their native BIM environment. This is in line with current best practices for BIM application (Bos, 2012). Reference models help to clarify who is responsible for which part of the model. The imported model, after being further optimized, is then linked to a separate project file for the modeling of an HVAC installation, using a series of custom *Revit Family* objects, kindly provided by a regional engineering office. Ideally, the HVAC model is assembled again with the design model of the architects, but this was left as optional.

For the local collaborations, the exported IFC model is used to create a qualitative and quantitative assessment of the model, which is returned to inform the design team about possible model improvements. This includes clash detections (element overlaps), verification of model completeness, project validity and checking against a prepared building regulations rule set.

In both types of collaboration, we completed a full feedback-loop, in a model-based workflow. While such a workflow might be a bit simplified, compared to expected future professional exchange, students are learning several important characteristics of design collaboration: description of exchange requirements, preparing models for a particular goal, cross-checking the exported information and learning about means to improve the model preparation. By introducing students to such processes, they are being prepared for a future construction industry and might be able to introduce this knowledge in the offices they will join in a few years.

Experiences about the didactic and digital communication aspects of the collaborative work are elaborated by the authors in another conference paper (Boeykens et al., 2013). There we describe more in detail the importance of the different modes of communication, the different roles that members in a project team take on and the experiences learned from a related collaborative assignment on "*Zero Impact Building*" between students of architecture and students of construction management, which was also undertaken during the COM.BI project.

Technical description of the collaboration

The collaboration in the architectural team used the *ArchiCAD TeamWork* functionality, which allowed all group members to work synchronously on the same model hosted inside *Graphisoft BIM Server* [4].

To be able to access the *Solibri License Server* and to sign in to the BIM Server from outside the university computer room, a *Virtual Private Networking* (VPN) connection is required. While this is provided by the university ICT services, it posed certain restrictions on the computer systems. The connection would only succeed if the operating system on the student laptops were up to date and equipped with a correctly configured virus scanner and *Java*-runtime. Unfortunately, some students were not able to establish the necessary VPN connection, due to technical problems. As a backup plan, the main computer classroom was fully configured and some teams needed to rely on this.

We encountered limitations when trying to keep the exported IFC model fully usable in the receiving BIM software. Since we cannot expect students to be aware of all peculiarities of particular IFC implementations in BIM software, possible problems are documented and, where possible, solutions are given that present better model exchange. The actual export requires additional configuration of the IFC writer settings, with direct impact on the usability of the model. This is also documented for students, to provide them with a usable starting point. It is very important that they experience the implication of the used configuration. In a *Coordination MVD*, the focus is on accurate geometry, enforcing the model to be exported using *Boundary Representation* (*BRep*) geometry. This has the disadvantage that the model will be completely static, preventing it from being further edited or corrected. Using *extruded* geometry on the other hand generates better editable objects, containing more IFC attribute values, but at the cost of a loss of certain model details. To assist this last step, students are obliged to perform

Problem Situation in Revit	Recommended Action in ArchiCAD
Objects lack properties	Enforce attribute export in *IFC Translator*
Walls become "*in-place*" families, Window/Door vertically offset from opening	Simplify geometry, e.g. remove *Solid Element Operations*, reveals, casing.
Orientation of walls, doors and windows not available.	Add custom IFC tag or agree on ID naming convention.
Spaces do not contain category	Add category name manually as added attribute using *PSet_SpaceCommon*
Walls do not connect to Sloped Roofs	Replace with legacy "*crop*" operation and convert multi-plane roofs to single-plane

Table 1
Overview of ArchiCAD model adjustments to improve IFC import into Revit.

Problem Situation in Revit	Recommended Action in Revit
Door and Window voids do not protrude through the wall volume.	Edit family object and extend void to wall façade.
Rooms get wrong height (= default value from template file).	List ArchiCAD Zone Height alongside Revit Room height and manually correct.
Identical windows and doors become separate Family objects.	Select and replace with appropriate family object (if desired).
Door & Window height attribute not set	Check extended IFC attributes for exported value from ArchiCAD

Table 2
Overview of some Revit model adjustments to re-create the ArchiCAD design model.

a visual check using an IFC Model viewer.

During the preparation of the learning material, a series of recommendations and known problems were documented, giving the students pointers to problems they might encounter. At first, before the IFC model is exported, the design model in ArchiCAD can be altered to generate more usable output, as summarized in Table 1.

Some aspects were not solvable within the design model, so in those cases, manual changes in Revit are required, as described in Table 2.

Even then, certain information was inconsistent and some workarounds were still required. In those cases, students were free to use other means to communicate the missing information.

Didactical learning material and facilities

As part of the didactical vision on the *Architectural Computing* course, which also comprised other themes (visualization, freeform modeling, digital documentation), it was decided that as much classes as possible would be replaced with video-tutorials. After a general introduction seminar, students follow the provided lessons at their own pace. While the recording of this material was a serious effort, student reactions were mostly positive. They appreciated the freedom to watch the material, rewind where necessary or even skip parts that seem unneeded to them. As the computer skills vary considerably between students, this was a valuable alternative to classroom-based tuition, which has become more difficult over the last few years. After students were given time to assimilate the tutorials, guided consulting sessions were organized, where students were able to pose individual questions, based on their own work. This was accompanied with an online forum for questions. An added advantage of video-tutorials is that they can be easily shared. They not only serve our own classes, but also attract many other users worldwide, since they were openly hosted as *YouTube playlists* [8].

Is it worth the effort?

While some of these aspects might seem rather trivial, they do pose a serious technical challenge to properly set up and we have been lucky to have full collaboration of the system administrators throughout the whole project. It also required a serious additional management effort of the teaching staff to e.g. set up user accounts on the TeamWork server and to assist with the ICT aspects of the exercise. It should also be noted that, even with more than 100 users, the system appeared quite stable and reliable and only some minor interventions were required. We are aware that such additional efforts and support are more difficult to impose on design studio teachers, certainly if they are not accustomed to BIM software and all required network functionality.

We are convinced about the value of BIM in construction and the necessity of learning BIM as a methodology in education. However, to appreciate these values, students should not only learn the theoretical basis. They also need to experience the BIM methodology in a realistic collaboration scenario and learn to use the software tools in an efficient way.

As part of the first BIM assignment of the architecture students, the focus was on understanding the concept and applying it in a practical context. Most of the students testified that they understood the idea of BIM, but not all of them were convinced about the effectiveness. Many students still fall back on their approach of using *AutoCAD* for 2D drafting and *SketchUp* for quick 3D modeling. The underlying theme was that BIM was often regarded as a software tool for 3D modeling instead of a collaboration method through the building process. They specifically mentioned limitations in modeling freedom, due to the indirect nature of describing geometry with parametric entities in BIM software. However, teachers should also not overestimate student maturity and insight into the design process, especially at the Bachelor level. Instead of enforcing the use of BIM in the design studio, for which there is no general consensus, at least in our schools, our process-based introduction will give students a more hands-on insight in how the BIM methodology could work, with obtainable objectives. The support with adequate learning material and sufficient technical facilities is essential.

Some people would argue that learning a specific BIM software tool is not the task of the university, but we have the experience that it is very valuable to at least learn the proper usage of one BIM software application in a practical context, which can be transferred to other software later on, if required.

EVALUATION AND FEEDBACK

Students are asked at several points in the collaboration exercise to reflect on the process and the applied techniques, using questionnaires and a logbook. In addition, their own role in the simulated design team is also evaluated.

The project results in two types of guiding documents. The process and project based documents are oriented to be used by students. The process-based documents are formulated as open questions instead of a fixed checklist, as to foster reflection and discussion among team members. For a more detailed description of the different guiding documents that were set up, we refer back to (Boeykens et al., 2013). In addition, we summarize the didactic guidelines towards educators. They are categorized into BIM, construction-related and domain-neutral aspects, e.g. organizing student teams.

Student feedback is also necessary to gradually improve the collaborations. As it is the intention that the collaborations continue after the COM.BI project-funding timeframe, we take their remarks and considerations seriously. We list some comments in Table 3 and how they are improved.

Overall, students noted that the collaboration exercise did not take an enormous amount of time and many groups finished their assignment before the deadline. The main intention of the exercise – a first-hand experience of how BIM could be applied as part of the design process – was clearly specified, avoiding students to spent excessive time on solving detail-problems.

It should be noted that the building model was not a new design, but rather a retake of one of their earlier design studio projects, to avoid the overload of the full design process, with conceptual devel-

Student comment	Afterthought
Assignments need to be clear and compact	Refine the assignment, limit requested documents/models/reports, be specific
Improve team coherence	Initial group meeting, esp. with external engineering students. Have them clarify their tasks to each other.
What should the model checker role do?	Add explanations about the rulesets.
Graphics in model checker look weird	Clarify software limitations. Model checker is not a visualisation environment. Focus on relevance in process.
Model geometry is not exact in model viewer/checker	Clarify that the purpose of a viewer/checker is different from a documentation tool.

Table 3
Comments and recommendations from student feedback.

opment and extensive teacher consults. It was explained that the architectural quality of the design would not be part of the grading criteria, because this was already done as part of the original design studio exercise. The quality of the model however, taking the received feedback into account, and the reporting were effectively graded.

CONCLUSIONS AND FUTURE OUTLOOK

All project partners are convinced that this is most valuable exercise, providing a huge experience for both students and educators. This approach illustrates BIM as a process, rather than as a tool. Students are stimulated to reflect on both the product (the design) and the process (the design collaboration in a Project Team). However, do not underestimate the need for continuous evaluation and the increased technical complexity to facilitate the collaboration. Luckily, the software tools, while not perfect, proved to be adequate and fairly stable. IFC support, while not perfect, due to implementation differences between software vendors, is gradually improving and is, indeed, "good enough" to be used at the core of the collaboration process.

It is very important to be clear about the expectations towards students, as the exercise should present them a positive experience with BIM and not blur this with an extensive assignment. The exercise attempts to capitalize on the virtues of BIM: synchronization of representations (all documents), extraction of information (schedules), model-based information exchange (IFC) and model evaluation (model checker). The formulation of the assignments and the final expectations need further refinement and valuable lessons were learned to improve the assignment for the next semester.

Several adjustments to the curriculum are initiated, to ensure a durable implementation of the collaboration beyond the period covered by project funding. All involved partners are enthusiastic to continue further, precisely as we seemingly are, in our Flemish region, at a turning point, where several professional, academic and commercial parties are increasingly moving towards BIM, which will form the basis for a regional knowledge network.

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Landscape Information Modeling

Plants as the components for information modelling

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Abstract. *In this paper we report on a recently started PhD project in which we investigate the extension of the concept of "Building Information Model" (BIM) to the domain of landscape design. The potential benefits of BIM in the field of architecture have been reported many times (e.g., Ibrahim et al., 2004; Eastman et al., 2008; Abdelmohsen et al., 2011). However, in landscape design an information model in the way of BIM seems to be missing. Benefits of a Landscape Information Model would be (a) formalisation of knowledge in landscape design; (b) information model to support multiple participants in landscape design; (c) improved information exchange between landscape design, architecture, and urban design. In this paper we set out the basic outline of the research.*
Keywords. *BIM; landscape design; LIM.*

LANDSCAPE INFORMATION MODEL

In this paper we report on a recently started PhD project in which we investigate the extension of the concept of "Building Information Model" (BIM) to the domain of landscape design. The potential benefits of BIM in the field of architecture have been reported many times (e.g., Ibrahim et al., 2004; Eastman et al., 2008; Abdelmohsen et al., 2011). As a technology, various instances of BIM can be found throughout many applications in the Building & Construction Industry. To the best of our knowledge, there is no similar application of the BIM principle for landscape design. In our view, there are three major benefits in the application of BIM principles to landscape design:

- Provision of an information model for the domain of landscape design.
- An information model that would support multiple participants in the landscape design process.
- Integration of landscape design with urban and building designs.

In our research project, creation of an information model for landscape design proceeds in two phases: first, the definition of an ontology of relevant concepts and objects for landscape; and second, the formalisation of this ontology into an information model. This process allows knowledge capture and representation which right now is not available.

Similarly as in architectural and urban design, in landscape design multiple parties are involved (landscape designers, municipality, urban planners, and so on). Reliable exchange of information during the design, realisation, and management phases will increase effectiveness and reduce errors and the risk of (costly) corrections.

Finally, when an information model for landscape would be available, it would allow easier integration of landscape design with urban and architectural design through exchange of information models. This is important to note, because landscape design is naturally involved in urban structures: parks, green areas, public spaces, and the immediate surroundings of buildings are often subject of landscape design. Therefore a more fluent link through a Landscape Information Model between architecture, urban design, and landscape design would be very beneficial.

CHARACTERISTICS OF LANDSCAPE DESIGN

In our view, a landscape information model consists of two major components: first, the information and knowledge about sites (terrain, ground conditions, weather, micro- and macro-climate, and so forth), and second the information and knowledge about landscape objects ("soft" materials such as vegetation, and "hard" materials of built objects).

Landscape design is a multi-disciplinary field in which areas such as ecology, geography, geology, horticulture, and botany are used. This means that knowledge from quite a lot of areas has to be captured in an information model. Because of the biological nature of landscape design, it is inherently dynamic in time: changes in the terrain, weather, and most of all the "soft" materials have to be taken into account. Therefore the design of a landscape does not just feature a "final" or "fixed" state, but more resembles the design of a process in which the individual development of components and interactions between components have to be balanced.

LANDSCAPE AND NATURAL ELEMENTS IN URBAN CONCEPTS

Landscape design in urban structures serves the following purposes:

- Maintaining and enhancing ecological stability.
- Maintaining and enhancing ecological biodiversity.
- Protection of soil (environment for the realization of natural processes).
- Protection of natural monuments and valuable and threatened species.
- Management of water regime.
- Hygiene environment (in particular attention to air pollution, noise and dust fallout) - transport solution.
- Care for uniqueness, aesthetic and cultural values of landscape identity.

The functions of greenery

The "soft" materials (greenery) have a distinct role in the design of landscapes (Sklenička, 2003):

- Environmental (system of wildlife corridors, insulation - emissions and partly noise, regulation of temperature and air humidity, air flow - acceleration due to temperature differences between greenery and buildings, sanitation - clean air, produce oxygen, ...)
- Recreational, aesthetic, social.
- Water managing.
- Soil-protecting, meliorating.
- Architectural -creation of space - part of the urban image (counterweight to artificial urbanized environment).
- Economic - production.
- Microclimatic.
- Fire-preventing.

We can distinguish between greenery in main function, and in additional function. In the main function, greenery is applied in parks, natural non-forest areas, cemeteries, gardeners, green insulation, botanical gardens, and zoological gardens. In the additional function, greenery is applied in residential areas and private green spaces. Our major focus will be on greenery in main function.

Compositional elements of garden and landscape architecture

The compositional elements of garden and landscape architecture consist of technical elements ("hard") and vegetation elements ("soft").

The technical elements are:

- Terrain.
- Water (water features, irrigation, drainage).
- Solid surfaces, paving.

- Exterior furnishings.

The vegetation elements are:

- High vegetation - tree layer.
- Medium vegetation - shrub layer.
- Low vegetation - ground cover plants, lawn, herbs (perennials, annuals).

Vegetation is a live, volatile and organic component of the composition and it is dependent on the conditions of surrounding environment. When designing the garden/landscape we have to take into account all the conditions that could possibly affect the behaviour of the vegetation elements.

Conditions for inclusion of vegetation elements in the architectural design

Here we have to begin with the introduction and acclimatization of species. In the region of central Europe there are about 80 native species but more than two thousand non-native species can actually grow here.

When some foreign species are introduced we have to let them adapt to local conditions. According to E. Quitt (1971), our region has several climatic regions:

1. VT - very warm, dry (average temperature 9-10°C, annual rainfall 500-600)
2. T1 - warm, dry (a.t. 8-9°C, annual rainfall <500)
3. T2 - warm, light dry (a.t. 8-9°C, annual rainfall 500-600)
4. T3 - warm, light humid (a.t. 7-9°C, annual rainfall 550-700)
5. MT1 - moderate warm, dry (a.t.7-8,5°C, annual rainfall 450-550)
6. MT2 - moderate warm, light dry (a.t.7-8°C, annual rainfall 550-700)
7. MT3 - moderate warm, humid, lowlands (a.t.7-8°C, annual rainfall 700-900)
8. MT4 - moderate warm, humid (a.t. 6-7°C, annual rainfall 650-750)
9. MCh - moderate cold, humid (a.t. 5-6°C, annual rainfall 700-800)
10. Ch - cold, humid (a.t. below 5°C, annual rainfall over 800)

Vegetation is distributed according to their ability of growing in the similar climatic conditions. This is called zoning.

ASPECTS OF TREE VEGETATION CLASSIFICATION

In the following section we provide an overview of generally conceived major properties of tree vegetation that may form a starting point for a general information structure (Michálková, 2011) (Table 1).

The dynamic character of the vegetation elements

As we mentioned previously the vegetation is very dynamic element of the design. We have to predict its changes during the whole life-cycle (size, shape) as well as its seasonal cycle.

- Development/growth: Youth, Period of fertility, Period of death.
- Reshaping: compact design changes in the last stage to the irregular shapes.
- Seasonal cycle - behaviour, requirements, and appearance throughout the aspects of spring, summer, autumn, winter.

OUR APPROACH

The strategy of the research project consists of two parallel tracks: one track is breadth-first and top-down, in which we aim to comprehensively describe the domain of landscape design; the second track is depth-first and bottom-up, in which we aim to develop specific information models for representative components of landscape.

The top-down approach provides the general framework for the landscape information model, and ensures that we do not oversee relevant aspects. The bottom-up approach ensures that we can define realistic and applicable information models.

BUILDING INFORMATION MODEL

Although Building Information Modeling (BIM) has its roots in the mid 1980s, its popularity within the Architectural, Engineering and Construction industries has risen only recently- that is reason why in-

Composition type
• Basic, skeletal trees - long-living they stay on the spot throughout the parks lifetime - oak, linden, maple, elm. • Additional trees. • Filling, temporary - fast-growing species. • Under-layer (middle and lower floors). • Ground covering species.
Visual characteristics
• Size. • Habitus (shape variable within species). • Structure. • Texture - the period of dormancy. • Color - foliage, flowers, fruits.
Size of tree
• Small 5-10 m fruit trees, ornamental cultivars. • Medium 10 (15)-20M hornbeam, birch, rowan, birch, spruce, pine, fir. • Large 20-30 (40) m to 40m: Buba, lime, ash, poplar, elm, maple.
Branching structure
• Branching dense, sparse. • Direct branches, gnarled.

Table 1
Aspects of tree vegetation classification.

formation modeling is still being developed for the buildings mainly - the construction management and facility operations.

That may explain that in our investigation we did not find any indication of existence of a survey or a research in our direction. Firstly we needed to get a deeper knowledge of the term "BIM" and also the software that supports this system of work.

What we found about BIM could be generalised to this: Building Information Modeling covers more than geometry- it extends the traditional approach to the building design (two-dimensional drawings as plans, elevations, sections, etc.) beyond 3-D to time as the fourth and cost as the fifth dimension, and sixth dimension is the life cycle management. It also covers spatial relationships, light analysis, geographic information, quantities and properties of building components (for example manufacturers' details).

There are two major BIM software developing companies Graphisoft (ArchiCAD) and Autodesk (Revit) that bring their products to our market. Additionally there are also Nemetschek (Allpan Architecture) and Bentley (Microstation V8i).

LANDSCAPE MODELLING SOFTWARE

We have found several smart "CAD based" programs, but all of them are used for 2D design (the traditional way). One case is for example ArborCAD, which is special purpose CAD software for the needs of arborists. It is based on the landscape software LANDWorksCAD. It has a lot of features specially aimed at information about plants, trees, and their properties.

Additionally there are also some applications that work with plants as dynamic objects:

- NatFX is a plug-in (for Alias|Wavefront's Maya) designed for modeling and animating 3D plants (age, season, and scale). Animation is possible either as a realistic effect (with botanical constraints) or as a cartoon effect (by-

Table 1 continued
Aspects of tree vegetation classification.

Foliage texture
• Texture fine (small leaves) • Coarse texture (large-leaved trees - maples, horse chestnut, sycamore) • Airy texture (platane).
Growth and growing characteristics
• Age. • Growth rate. • Environmental requirements.
Lifetime
• Short-living (about 80 years ,willows, poplars, alder, birch), fast-growing. • Average, (200-300 years, maple, hornbeam, rowan, spruce, pine), survivor type. • Long-living (600-800 years, oak, linden, beech, yew).
Environmental requirements
• Temperature: thermophilic (oak, beech, maple), cryophilous (spruce), no particular requirements- pine, birch, sycamore. • Moisture: Xerophilic (rowan tree), Mezophilic (ash tree), Hydrophilic (willow). • Light: Heliophile (larch, pine, birch), Average, Heliophobic (yew, hornbeam). • Nutrients: most of the plants have average demand for nutrients, but some may demand alkaline soils - Addition of Ca or acidic that requires addition of peat. Some species tolerates salinity - that ones are suitable for street alleys (acacia).

passing the constraints), using natFX's built-in plant skeletons. All natFX trees and plants are fully textured, based on scans of actual leaves, stems, and bark. NatFX is currently available as a plug-in.

- EASYnat by Bionatics is an add-in that can be used within AutoCAD or 3Dmax. Currently the trees are parametrically generated from the input data (height, width, age and season) (Figures 1 and 2).

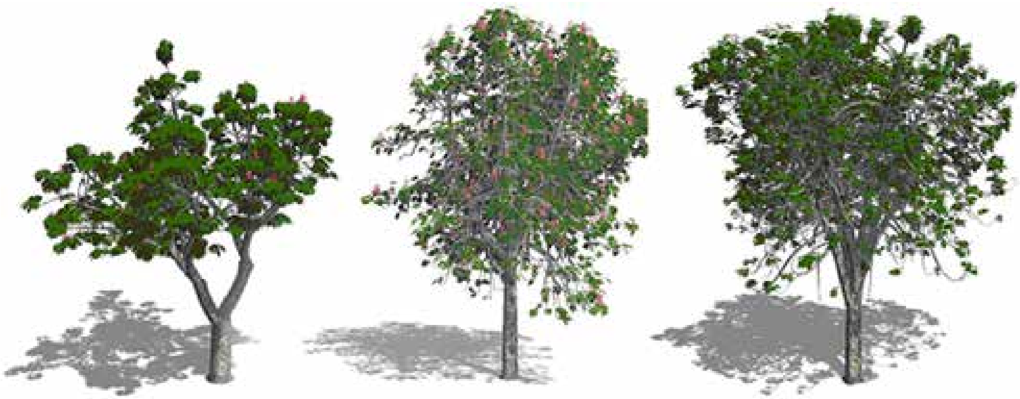

Figure 1
EASYnat examples of renderings of the Horsechestnut tree models.

Figure 2
EASYnat simulation of a growth of a Horsechestnut tree.

EASYnat could be suitable for our further research - for implementation into object orientated software like Revit or ArchiCAD and development of their attributes and actions. The plants should have more attributes and while simulating the grow process, they should react and interact with its surroundings.

UNIFIED MODELLING LANGUAGE

BIM involves representing a design as combinations of 'objects' that carry their geometry, relations and attributes. Such objects and relations can be described by UML (Unified Modelling Language). UML is a standardized general-purpose modeling language in the field of object-oriented software engineering. It is a tool for defining the structure of a system through several types of diagrams. UML enables to model an application specifically and independently of a target platform (Fowler and Scott, 2000; Blaha and Rumbaugh, 2004).

UML diagrams represent two different views of a system model: static (structural) and dynamic (behavioral) diagrams (Schmuller, 2001). There are more than ten different types of UML diagrams. In our inquiry we are interested in class diagrams, object diagrams and activity diagrams (Figure 3).

In our research we aim to advance the information model of the vegetation to be comprehensive. This means that we not only model the general attributes of vegetation (for example for trees family, genus, species, cultivar, decicious/evergreen, season), but also the time dynamic attributes (for example for trees height, canopy perimeter, trunk perimeter), surrounding reaction (for example for trees soil requirements, geographic location, moisture), and interaction (for example for trees spread, ecologically close trees, and antagonistic plants).

In real life coding examples, the difference between inheritance and aggregation can be confusing. If you have an aggregation relationship, the aggregate (the whole) can access only the PUBLIC functions of the part class. On the other hand, inheritance allows the inheriting class to access both the PUBLIC and PROTECTED functions of the superclass.

DESCRIPTION OF POTENTIAL APPLICATION OF UML DIAGRAMS

We have applied the class diagrams to our study case: we needed to state the classes and all the atributes that our classes should have. Then we have created one instance of that class and the relations (Figure 4).

These diagrams we use to map the classes that appear in our application study. While describing the plants as object for BIM you have to take in account all their properties and attributes -such as height, perimeter of canopy, perimeter of a trunk, classification in the meaning of family- genus- species- cultivar, to state if the plant is decidious or evergreen, the aspect of season (mainly to state the existence and color of the leaves), the age of the plant and its habitus an finally for most efficient work with the objects the detailing and the way of graphic appearance.

Figure 3
Activity diagram.

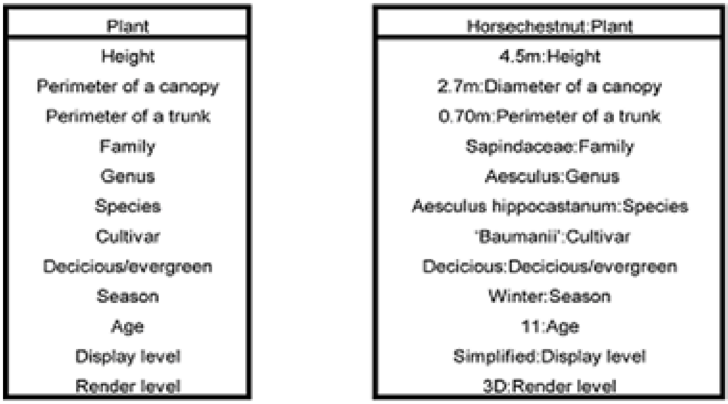

Figure 4
Class and instance diagrams.

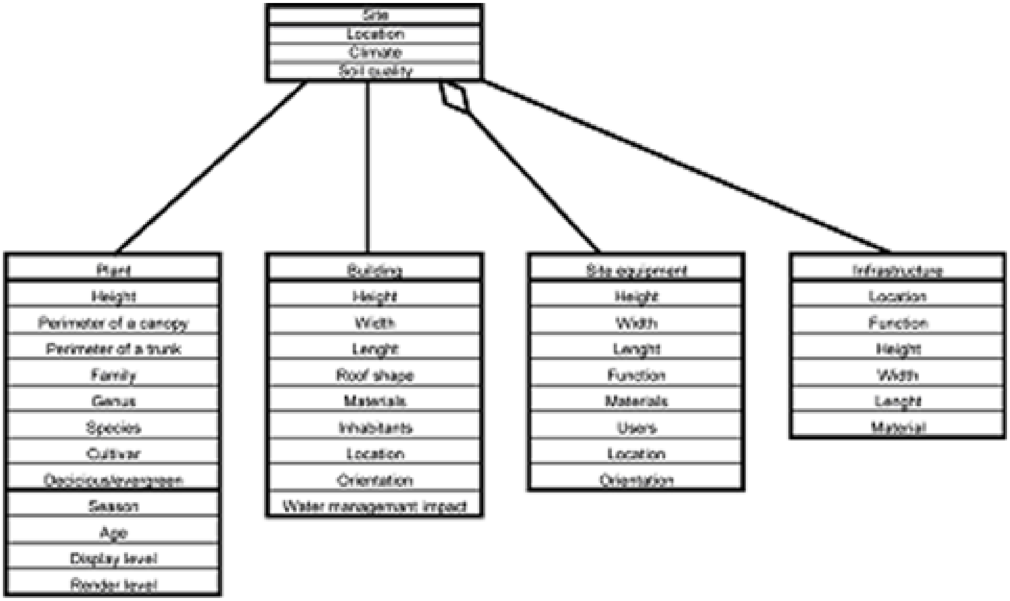

Figure 5
Diagram of relations between classes.

The same (properties and attributes) we should state for the other objects that we would like to involve in our application.

In this preliminary diagram (Figure 5) you can see buildings (can cover the minor architectural works in the countryside), site equipment (such as benches, trash cans, lightning, equipment for cyclists-parking places) and infrastructure objects.

DISCUSSION

In the paper we have presented our first findings towards a Landscape Information Model. The work is still in a very preliminary phase, but we hope to have laid some foundations. As trees are dominant visual elements in landscape design, we have started with more concrete knowledge capture of trees. In the next steps we aim to implement a parametric data model of trees in Revit.

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ifcModelCheck

A tool for configurable rule-based model checking

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Abstract. *On behalf of the BBR (German Federal Office for Building and Regional Planning) the development of an Industry Foundation Classes (IFC) based inspection tool was accomplished as application on an underlying work-in-progress development framework. By providing a machine-based checking process the tool ModelCheck was rolled out to meet demands emerged during pilot projecting. Thus it is capable of processing automated compliance checks on quality criteria for the authorities, e.g. documentation guidelines of BBR regarding building and real estate documentation or building information modeling (BIM) quality criteria formed for the Humboldt-Forum project – a BIM pilot-project managed by BBR. ModelCheck supports checks on IFC models - formal against schemes and logical inspection with regards to alpha-numeric content by using xml-based configurable rules.*
Keywords. *BIM; quality assurance; rule-based model checking; collaboration*

INTRODUCTION

Besides being a promising concept from a general point of view, building information modeling (BIM) in real world is still confronted with problems in terms of overarching business and process related co-operation on a base of its models. The results of a market analysis regarding potentials and hindrances of BIM application in Germany identify great prejudice and reticence coming to business overarching transmission and cooperative usage of BIM models (von Both, 2012). In the market the benefit of BIM in terms of co-operation with project partners is worse than other more operative aspects by far. In such co-operation activities nowadays one reason, besides inadequate technical interfaces, seems to lay in insufficient specification of exchange conditions and qualities of model data respectively building information.

Thus, the participants of the survey highly agreed (65%) to the statement that the quality of digital building models in form and content is not adequately standardized yet (Figure 1).

The specification of such defined process interfaces can be mentioned here as an important precondition for a simplified and secure contracting and cooperation: By referring to normative descriptions contracts can be concluded very efficiently and securely between client and planner respectively contractor as well as among the planners themselves. This becomes very important when the contract partners – like in Germany – are composed newly for each project.

On one side Germany's Architecture, Engineering and Construction (AEC) sector addresses this problematic situation on a normative level by discussing a development of a set of standard specifications with regard to contents and process related quality criteria describing building models. On the other side an increasing number of larger construction companies and general contractors among practitioners have already started developing internal (process related) standards of quality. These are used as mandatory basis for co-operation towards project partners. Though the German authorities have also developed generalized quality guidelines, for instance the 'Dokumentationsrichtlinien für den deutschen Gebäudebestand' (documentation guidelines for German building stock (Figure 2)). These are capable of describing - in a BIM context - the execution of existing quality requirements in form and content. A main part of this directive is the alphanumerical building description that includes the constructional as well as the technical room data sheets. Thereby 'article' (countable types of furnishing respectively equipment that can be specified with further properties) and 'feature' (abstract definitions of objects' properties) are fundamental structures for description. Equal characteristics of plots, buildings, spaces, equipment etc. are described with a uniform code of property.

Uniqueness of quantity-on-hand data has to be permanently assured by all involved stakeholder in order to guarantee consistency towards forward projection with the streamlining exchange of digital building information data (coding of plots, buildings, floors, spaces and if necessary identification numbers) [1]. Thus corresponding concepts for process-accompanying quality assurance in the context of BIM were developed and exemplarily evaluated in pilot projects.

In the pilot project Humboldt-Forum (HUF) initiated by the Federal Office for Building and Regional Planning (BBR) quality criteria referring to this directive were specified. These criteria do not only regard to a future use of model data in facility management, e.g. space coding, topological allocations etc., furthermore they also cover important information for materialization and cost-estimation processes, e.g. part submission warrant and material coding.

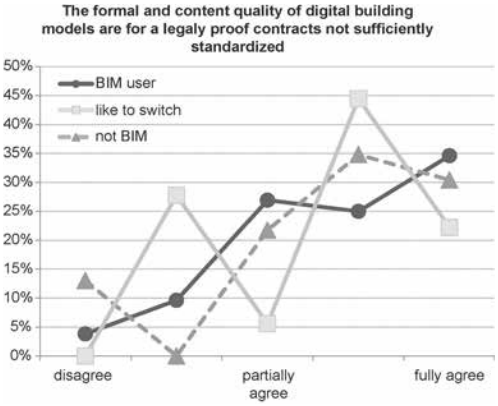


Figure 1
Agreement to the statement that the quality of digital building models in form and content is not adequate standardized yet.

Toward this quality standard a first step was taken by developing appropriate checking reports that enabled a process accompanying inspection and evaluation of model data received by project partners. Taking exchange scenarios into account, prior defined in the contract agreement, a process-accompanying quality control process was able to be executed. However, in the context of the HUF project manual (with eyes) quality control of the acquired alphanumeric criteria proved to be very extensive and ineffective. Thus a demand clearly emerged for suitable tools regarding model management and alphanumerical model analysis respectively model checking. The special need was to enable process-accompanying capabilities of generically rule-based semantic inspection of BIM models. After a market analysis it became obvious that so far none of the available tools had been able to satisfy the special demands of the authorities like a high level of flexibility and dynamic references. The business models

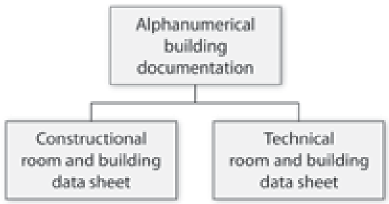


Figure 2
Detail from documentation guidelines for German building stock.

of the available tools did also not allow a flexible extension of the rule sets - they mostly only support a configuration of already existing basic rules. The implementation of totally new rules requires a charged development order. Thus, the BBR decided to develop own adapted BIM model checking software in cooperation with the KIT to extend their IT-infrastructure and meet their specific requirements.

REQUIREMENTS AND SOFTWARE CONCEPTS

Prefacing the description of the tool development, crucial requirements will be subsumed on the technical side and crucial aspects of the software conception are pointed out. Besides a brief overview on the technical implementation, the concept of rule configuration is subsequently presented more detailed.

On the technical level, the above derived logical requirements were further divided in those concerning the HUF context and the ones with regard to content. In terms of BBR – aspects related to actively running processes of the overarching BIM context in the ongoing HUF pilot project on the one side and on the other side the content- and organization-related approaches needed for implementation of automated compliance checks on documentation guidelines contents in process-accompanying BIM-model use cases with a long-term perspective on deriving robust internal IT standards results of the pilot projects. For BIM this meant the conception of a well reachable and compact workflow in order to organize the discipline-overarching data exchanges. Contrary, on the side of developing and managing generic rule repositories for documentation guidelines, flexible 'organizing'- functionalities stood alongside with requirements regarding the user's autarkic manipulation of rule logic in the focus of conception. Both levels of requirements were thematically separated and developed into two final versions of the software.

At first a clear conception guideline for development was given through the clearly described operative focus on one central workflow on the requirements side. This model checking workflow meant to be carried out by users without specific knowledge required - therefore developing aimed at a lightweight tool as a so called 'standard' version. In four steps it should be possible to load a model file, check its contents with chosen rules from a given repository and finalize a result report that can be exported as Excel-XML. While focused on the implementation in the HUF project it was meant to streamline first practical experience on BIM application by BBR.

The deduction of the development steps from requirements for the proper checking tool was confronted by an opposed development task – a rule configuration conception for BBR. A complex requirement level with emergent outcomes to be considered stood at the core of this task. For instance, technical implementation and maintenance of machine-readable logical contents did require designing totally new workflows (developing rule, maintaining repository etc.) accompanied by the need to define the new user roles (model checker, rule administrator). Setting up the overall conception had to be considered as a fuzzy context of future usage (after implementation in pilot project). Beside these 'invisible' requirements, future user/user's structures is unknown at the time of defining specific tool functionalities – all requirements for managing and manipulation of rule logic share common grounds e.g. need at different granularity of different previous knowledge on certain sets of circumstances (knowledge of model, knowledge of rules, knowledge of use case workflows etc.).These identified kinds of overarching concerns made it necessary to consider in the overall conception, the very diffuse yet universal requirements for the user interface logic of the software.

At last are the specific demands condensed in seemingly arbitrary requirements, for instance the reduction of inspection to only a part of the subject matter (IFC model instance), because of BBR's over time evolved structures. So while all rules concern the alpha-numeric part of IFC-model, this relates in terms of content to the requirements regarding the rules to be checked with the software, as they deflect documentary guidelines with regards to content that were first adapted for BIM context and then transferred into generic rules for model checking. Regarding IT infrastructure, BBR already had software for checking model geometry (clash detection), which was not capable of providing sufficient user-specific configurable inspection of model semantics. In contrast to heavyweight/monolithic proprietary checking software that fail to support users with full autarkic rule development capabilities on behalf of large functionality range (geometry and semantics), causes a high level of complexity in terms of rule layout e.g. Solibri [2]. In a long-term perspective for instance, a central requirement was to keep this generic rule repository up to date by own means - in case of further developments in federal guidelines regarding buildings. Thus development aimed at a freely configurable and manageable user's rule base.

By especially enabling a separation of concerns between the knowledge of model users put into rule developments, and developers taking care of software related maintenance regarding the inspection shell, it/this seems to be the better business model as compared to mixing these concerns. Finally, the aim was integrated in the software conception by physically decoupling of the rule logic from the inspection-shell tool (business logic), and placing it in open described xml schemes describing the user's domain-specific rule logic.

IMPLEMENTATION AND USAGE CONCEPTS

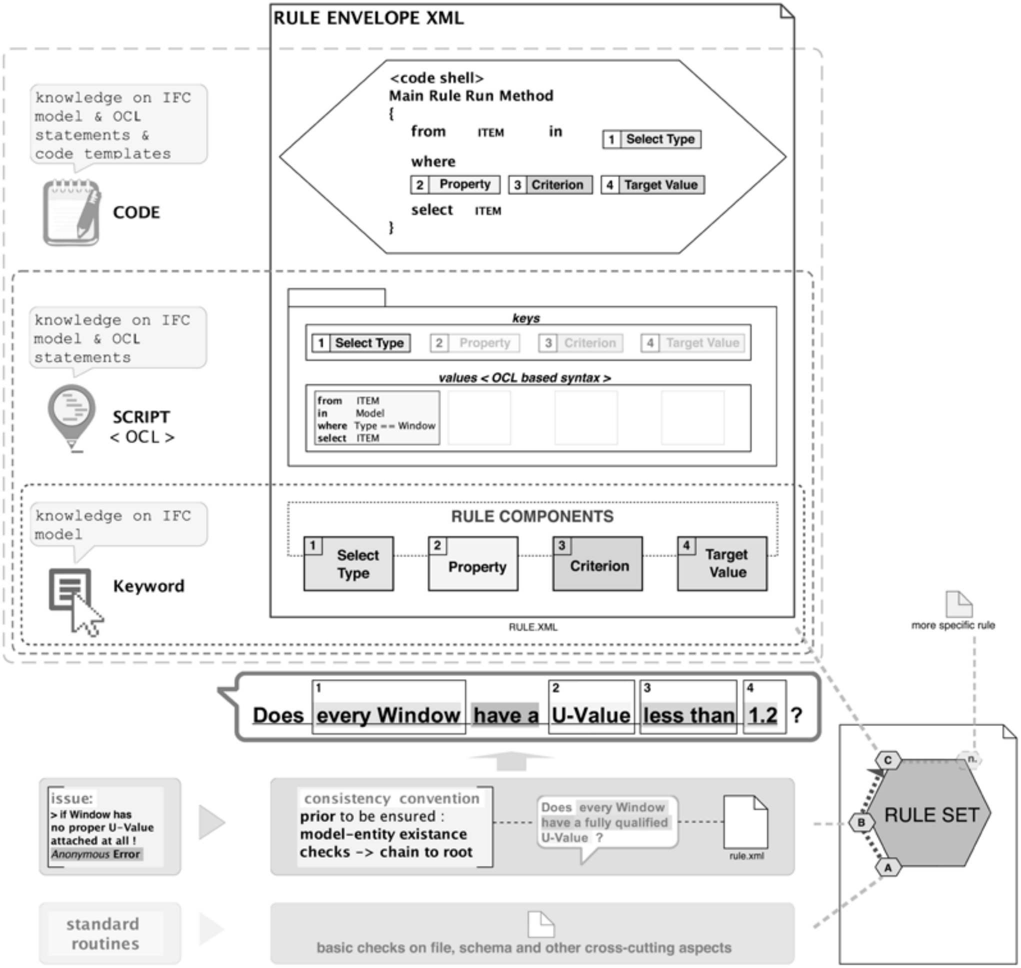
Besides serving BBR as a tool (standard version) in practice with ad hoc revenues within the HUF project, having all rule logic at hand (admin version) stays warranted if enhancements in rules take place because of acquired experience in practice over time that the user can successively put all together – self-tailored for internal workflows – into a common rule library and manage it from there.

Strategically it had been considered to implement the standard version as a subset of the extensive administration version. In this way, the rule development environment always has the model checking functionality at hand as needed for testing and verifying rule logic. Again placing the management of rules in the separate version generally provides a base for robust user's structure – e.g. versioning control separated from usage of rules.

In order to present the logical integration of the management environment *rule library* on a macro level e.g. the user-regarded convention-based frame settings, with the manipulation environment *rule configuration* on the micro level e.g. code, notations, standards, derived conventional settings, a bottom up approach will illustrate the latter level on behalf of the constitution of a rule respectively crucial aspects into turning logic to automated compliance checks e.g. as a cross cutting concern of the convention on how one rule logic expands over several rule files.

On the bottom level, the logical counterparts to the main XML tags in a rule file refer to loosely coupled constitutes of one logical clause – a so called *rule envelope*. All assigned rules with regard to contents were therefore decomposed in rule components that serve as elements in a model kit – embodied in the *rule configuration*. An overriding ‚orchestrating' algorithm, that is distinct according to the issue of the rule logic and sets the logical parts of the specified rule clause in relation to each, other respectively condenses the parts to the above introduced serial process-able check workflow. As in every rule file components are linked likewise to a checking workflow on the level of the beneath 'code skeleton' (cloze with wildcards for the return values of the rule components), a set of core templates were introduced as basic rule envelopes. Every variegated rule is derived from one kind of query at the core - in other words this origin (basic rule) connects all other sibling rules in the tool to each other. Allocating one basic approach to each general central questionings gives the user a decomposition principal at hand for formation respectively further development of the own rule repository and eases editorial aiding of a current state through elimination of redundancies.

Figure 3
Software conception: logical contents of rule XML.



Along the basic structure of an example rule (Figure 3), the rule components will be introduced. The decomposition of the components, hence the basic structure was thereby adopted from the Object Constraints Language's (OCL) main statements [3] in order to promote a convention-driven limitation to the source code used in the user's rule files by only implementing common templates.

Regardless of the user's knowledge, a verbally represented questioning (in the example: "Does every window have a U-value less than 1.2?") can function as an initial point of the rule development. In a first step, the rule administrator dismembers this concrete question according to the four components of the check workflow. Depending on a basic population of all components embedded in the rules of the repository, it can at this stage already be possible to suit the logical clause of the rule, only by choosing existing instances of components and if applicable alter the specific values.

Specific quantities of element instances are already gathered during loading the model in order to show a brief summary on the model content. These can also be adapted in the components by referring to their specific keyword. In cases where specific quantities are not set up at start nor defined in another rule's context, the rule administrator alter a similar query or create a new one. Thus specified in the so called Select Type component, the related congregation of instances is being hooked to a main iteration mechanism/slope in order to check a circumstance on each of the selected IFC Type instance.

Further specification of a property to the prior chosen IFC type is defined in the so called Property component (in the example: the pointer to the U-Value in the property set of the window type). So far the specified components will allow the main iteration through specific actual values of the selected congregation - in order to check these values, a corresponding desired output of the value is assigned in the so called Desired Out/ Target Value component. By defining an appropriate condition for the relationship between actual and targeted value in the so called Check Criterion/ Criteria, the last part of describing the rule clause is accomplished. By standard, this now fully specified checking workflow will return all elements of the congregation that do not meet the specified condition – a subset with error prone instances. In order to achieve a comprehensive output of the checking results, the so called Result component can be adjusted by specifying a suitable error description as a cloze with wildcards for crucial single values to clearly outline the returned error prone circumstance. With access to functions of standard version for model checking and functionality for verifying of developed rule, the rule configuration is set up with all necessary means of editing. This is streamlined by a concept of usage (UI) which is decomposed in different levels aligning with required stages of user's knowledge.

At the structural base of the hereinafter described concept of the knowledge-oriented usage strategy for dealing with complexity of involved matters, stands again the decomposition into the above mentioned rule components. Three access levels (in Figure 3: dashed lined boxes) are provided to the user in the rule configuration. In every higher level thereby – as a further abstraction of complexity - less knowledge is required to manipulate rules with regard to contents. However, this abstraction is again streamlined by limited amount of editing possibilities. Only elements that have been previously defined in the level below can therefore be referred to in the higher level. At the top level, keywords enable the cascading/coverings of complex logic to the unseen background. On this level it is possible to create variants of existing rules only with combination of given components and knowledge of the rule constitution. When additional object quantities are needed, domain knowledge of the constitution of the model to be checked is already crucially required – the only further knowledge required is on how to handle the statements, as described by the OCL standard.

In a middle level queries are therefore described in OCL-conform syntax and made referable by a self-chosen synonym (keyword for the top level), together they are persisted in the XML rule file as key-value-pairs. Knowledge to its full extent – rule constitution, domain-related as well as application of the code skeleton being used (basic rule template) – are only crucial on the ground level in order to create or extend the basic rules. With this concept at hand, the BBR staff is on the one hand in the position to ad hoc address different questionings within the HUF project on a base of manipulating the rolled out basic rules, and they are on the other hand in a long-term perspective by gathering necessary expertise over time, so that the user can then be enabled to maintain and further develop rule repository on own means.

Through inclusion of the configuration environment with the rule repository in the hereinafter described rule library environment, an overarching management of the development work on base of the rules is ensured. Bound by convention - all rules are obligatory referred to by at least one rule set – in the rule library environment the user is provided with manipulation functionalities of rule sets only. By the ability of individual assignment of rules to respectively different sets, a user-specific structuring is also enabled e.g. project-oriented. The structuring of the own rule repository is on the technical side supported by a technology known from common Integrated development environments (IDE) for dynamically compiling and executing rule code during runtime of the tool. Thus this enabled physically decoupling the user-specific logic concerning knowledge on model domain, rule repository, workflows etc. from the checking shell, since the current repository is loaded from the XML database at runtime only. Therefore, the own rules can also be structured and managed independently of the tool, if for instance there is available infrastructure like Content Management System (CMS) etc.

A basic structuring along the domains of the checked models was loosely integrated by strictly keeping XML parsing separated from checking mechanism in business logic and user-domain logic. Since the tool initially construed for checking the IFC XML standard already at core of basic rule development, a latter decoupling of basic XML-operations from the domain-specific aspects was focused. The basic rules that were therefore rolled out with the software, give the user a solid base to start an own robust repository from. Thus in terms of different future demands, it could also be further developed in a model-overarching manner.

As pointed out in different aspects covered above, making the software more flexible on the technical side is crucially accompanied by transferring of logical and structural responsibility to the user as well. This means for instance that before checking specific details, all model-instances involved have to be checked whether their instances are completely implemented in the way the specific rule refers to them. Since a non existing instance of a model element will not be recognized as error prone because of the fact that it is non existent, it is not covered by the questioning concerning its value check. In this case, the user has to warranty that inside the set of the specific rule, there is a prior rule that checks the existence of covered elements before the more specific check on the element value takes place. Since there are "chains" of existence checks for every specific rule in order to ensure the overall correctness of covered contents - all involved elements - there seems to be great potential for internally standardizing this issue and structuring it as a basic subset in the repository. Although turning the exhaustive responsibility for the domain-specific logic in the user's hand is accompanied by complexity in terms of managing the rule repository in the case of BBR application this seemed reasonable. Beginnings in the field of BIM model check research can be seen especially in countries were BIM-models are put to practice, for instance Balaban (2012) supporting Turkish authorities with automated compliance checks for fire guidelines. However segmented chains of requirements due to complex application contexts seem a common ground thereby. In order to achieve the goals mainly focuses get carried on very specific context-dependent solutions and therefor often show contradictive mixing of user and developer concerns. Hence they seem to be more vulnerable in a long term perspective; it is difficult to find a suitable allocation of developer and user respectively a suitable organization of the further development of the rule repository after solutions are implemented.

Because the pilot character of the HUF project in the usage of BBR, it was necessary to create a totally new rule repository. The separation of concerns was suitable since the user first has to build up expertise regarding different domain-specific disciplines. It enables thereby also successively gaining grip on the full functionality range of the software.

Other than these concerns regarding logical and structural responsibilities, all overarching concerns regarding plainly information technology were considered in the tool shell. Thus throughout all developing processes, a strict internal library-wide

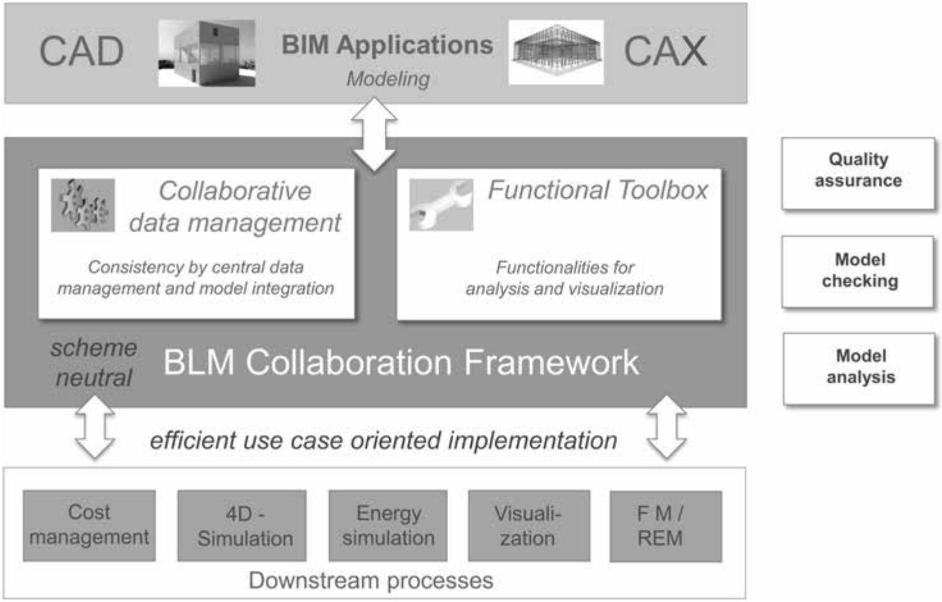


Figure 4
Concept of collaboration framework.

versioning keeps every applied rule with regards to content referable to every produced inspection result. This seems important e.g. it guarantees essential consistency for archiving purposes – older inspection reports are always mapped to the valid rule at time of inspection. Import and export functionality enables an administrating user to deploy newly finalized rules to users of a standard version that only use production ready rule sets. This allows team-internal organization of roles within a user group. Together, versioning and a project specific structuring enables parallel usage-oriented organization of similar rules in different contexts.

Putting ModelCheck into practice (HUF project) enables iterative evaluation and optimization regarding rule logic for the user – whereon further development of inspection shell functionality is then based upon. ModelChecks further development also takes advantage of extensions to the underlying framework, which will be briefly introduced hereinafter.

TECHNICAL BASE OF IMPLEMENTATION

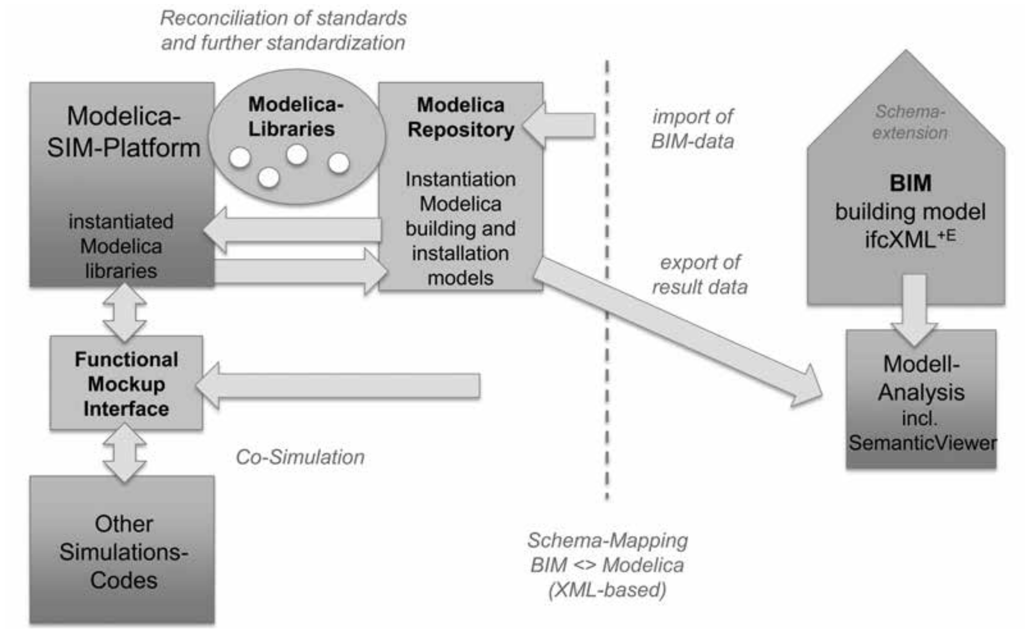
As an application-independent central service, the framework provides base functionalities for the model based data analysis. The base functionalities serve collaborative data handling, e.g. type- and attribute-oriented selections of partial and aspect models, integration of these partial models as well as supplying mechanisms for versioning, change management and transaction control (Figure 4).

Thus a kind of "Meta-Model-Server" is provided for further research and development projects that in different application scenarios can be implemented for different kinds of model standards like ifc STEP, CityGML or GAEB. Furthermore it supports model overarching model-operations (Hartmann and von Both, 2011).

OUTLOOK

Further development on the analysis and visualization components in the context of energy efficiency will take place within the science project "EneffBIM"

Figure 5
Conception draft EneffBIM project.



(funded by the German funding program "EnTools" released by the German Ministry of Economy) starting summer 2013. As seen in Figure 5, especially for the usage of dynamic energetic simulation, the logical content-regarding model analysis shall be the quality management vehicle for securing the interface from BIM to simulation.

With involvement of different Frauenhofer institutes (ISE and IBP) as well as the universities RWTH Aachen, UDK Berlin, KIT and buildingSMART on one side, the IFC model will be extended with energy relevant base types (input parameter) and suitable geometric representation forms. On the other side regarding energetic simulation, tools for co-simulation in the context of Modelica will be further developed and a synchronization of existing model libraries is been focused on.

Concerning model checking aggregated simulation results shall be led back in the BIM model in order to ensure better re-transition and evaluation of simulation results into the planning process and towards the layer of decision making. ModelCheck then serves as a checking and analysis tool for evaluation of variations with their different simulation results.

In this case a great meaning is beard to semantic visualization of simulation results (specific constraints of property values), representation of the range in values that exists in the comprehensive model and also checks on the characteristics of values.

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Daylight Performance Simulations and 3D Modeling in BIM and non-BIM Tools

Interoperability and accuracy – an experience aiming to a more integrated and interdisciplinary approach

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Abstract. *The fusion between building assessment and design can lead to better informed design decisions. Performance oriented design is better supported through the use of interoperable file formats for data exchange between BIM and non-BIM tools. At the same time, the parameters that influence the calculation during a performative assessment are no longer a purely engineering problem, since 3D modeling is of primary importance in defining the numerical output. The role of the designer along with the selection of the tools becomes all more relevant in this direction. A framework is presented hereby, which can be used for the selection between different BIM tools for daylight assessment. An insight is also given on the major parameters that can affect the outcome and on the obstacles that were experienced in four case-studies in relation to data exchange and information flow.*
Keywords. *Performance simulations; parameters; interoperability; daylight.*

INTRODUCTION

During the last years, there is an increasing demand for the integration of BPS (Building Performance Simulation) tools in the early design phase (Attia et al., 2012). The interoperability of BIM (Building Information Modeling) and non-BIM tools influences the workflow within the design team, while the building practice is progressively oriented to a more interdisciplinary approach (Augenbroe, 1992). The hereby presented study initiated as an internal research for the consultants of the company DGMR in the Netherlands, with the task to evaluate the three following daylight performance simulation packages; Design Builder v.3.0.0.105, Ecotect 2011 v.5.60/Radiance and DIVA 2.0 as plug-in for Rhinoceros NURBS modeler, and to provide suggestions for future use. All of the examined tools can provide dynamic daylight simulations under given conditions. The problems that consulting with the use of this software faces on a daily base, are related to incompatibility between the architectural 3D model and the simulation software, the long 3D modeling times and the error probability when complex geometries are involved. The aim is to acquire semantic information on the performance of the building over time, in a way that it can be integrated in the design process. The evaluation is based on the following criteria:

- Ability to simulate detailed and complex building forms
- Accuracy
- Interoperability of Building Modeling (IBM).

The above-mentioned criteria refer to two of the five major tools' selection criteria as defined by Attia et al. (2012) and incorporate the three factors that are given in the ASHRAE handbook:

- Capability of the tool to deal with the project requirements.
- Complexity of input.
- Quality of output.

Their selection for this study, reflects the problems with which engineering is confronted the most during collaboration with the architectural team for daylight assessments. At the present moment, it is common practice that the analytical model is derived from the architectural model after the extraction of a significant amount of geometrical data. Effort and long working hours are dedicated to the restructuring of the architectural model before simulating; and it is common that decorative elements need to be extracted, or the layering structure of the 3D model has to be redefined in order to provide appropriately defined layers where material properties can be accurately assigned. At the same time, the ability of the software to simulate detailed or complex building forms is closely related to issues of processing power and computing robustness and becomes clear that the building geometry that is used for performance evaluations has a direct impact on the calculation output.

A better collaboration between the design and performance assessment team is therefore necessary; in such a case the architects need to be informed on the effect of their model to the calculation process, so that they can structure it efficiently in order to facilitate, not only an accurate three-dimensional representation of the building, but also a fast performative assessment that can provide feedback for better informed design decisions. Regarding accuracy, in each of these tools, the output is the result of the connection of the imported or designed geometrical entities to a number of databases. The process can be analyzed through the following steps;

1. setting of the model
2. link of the model to the relevant for each case-study semantic information
3. calculation and presentation of the output.

Each of these steps presents a different level of accessibility and control potential for the user, the later becoming considerably limited as we proceed from 1 to 3. A fully controlled process would optimally lead to more accurate results, since parameters such as the geometry, material definitions or sky conditions would be fully editable, provided that the user is conscious of the influence of each parameter on the calculation output. Radiance provides such a possibility through a number of file formats (i.e., .rad, .dat), without posing restrictions regarding the computed geometry. An example on how a variation of the parameters affects the results is presented during this paper.

Ideally, data exchange would happen automatically in both directions, so that every alteration in the 3D model can change the simulation output and vice-versa (Kensek and Sumedha, 2008). In such a case better building performances can be achieved through a seamless back and forth process. Interoperability can be defined as the possibility of information exchange through interoperable file formats that allow for the use of the exchanged information Its importance lies on the possibility to diminish the time lost due to the exchange of data between the BIM or non-BIM modeler and the BIM tool.

In building practice, performance assessment is often carried out separately from the architectural design. The engineering team, is in many cases detached from the design of the building, while the architect uses assessments only as external information when compliance with regulations is strictly required. A better merging of the groups can be facilitated with a better collaboration of the software, so that both teams can refer to the same core models through interoperable file formats.

This study traces the flexibility of the examined software in importing and modeling 3D geometry

Table 1
Basic input data models 1 to 3.

Basic input, model 1 to 3				
Design Builder v.3.0.0.	NLD_Amsterdam. 062400_IWEC weather file CIE overcast sky	double glazing with airgap LTA 0.7	concrete ceiling, brick walls, wooden floor	Grid : 0.1m-0.2m Calc. plane: 0.7m
Ecotect 2011 v.5.60	NLD_Amsterdam. 062400_IWEC weather file CIE overcast sky	LTA 0.7	ceiling ref. 80%, brick walls ref. 50%, wooden floor ref. 20%	Grid size: 40x32x32cm Calc. plane: 0.7m
DIVA 2.0	NLD_Amsterdam. 062400_IWEC weather file CIE overcast sky	double glazing low-e	generic ceiling ref. 80%, generic wall ref. 50%, generic floor ref. 20%	Grid-nodes' density 500x800 Calc. plane: 0.7m

and the range of deviations that can be expected during the calculation of the analytical model, and specifies the information that is being lost during the process. The Drawing Exchange Format (DXF) is hereby used as the basic means of design information transfer.

METHODOLOGY

For the needs of the present research three case-studies were used on the grounds of the following methodology; a base model was prepared and simulated in Design Builder v.3.0.0.105. This model was exported in .dxf format and recalculated in DIVA 2.0 and Ecotect 2011 v.5.60. Rhinoceros 3D-CAD modeler was used as a complimentary tool in order to model the missing export data. All the three packages were linked to Radiance and provided output based on the climate data of Energy- Plus _IWEC weather data files. The following input data were given for each one of the packages. The settings reflect the effort to use equal input data. Identical input is not possible at the moment due to differences in the software settings (Table 1).

The three case-studies refer to two on-going projects and to a simplified setting:

- Case study 1: a complex geometry (Figure 1).
- Case study 2: a purely orthogonal geometry (Figure 2).
- Case study 3: a simplified setting of a typical office space (Figure 3).

The common feature between the geometries is the linear form. They refer to two on-going projects and one simplified setting that is often met in everyday practice.

The simulation was oriented to one-variable approach in order to facilitate the comparison between the tools. With regard to precision, the following settings were used: ambient bounces (ab) = 2, ambient accuracy (aa) = 0.1, ambient resolution (ar) = 300, ambient divisions (ad) = 1000, ambient super-samples (as) as default. For the needs of this study, the Daylight Factor was chosen as the main calculation measurement; the prediction of the Daylight Factor under a CIE overcast sky condition is at the moment the dominant approach in evaluating daylight, despite the fact that it provides only a rough estimation of the yearly indoor conditions (Tregenza, 1980). Yet, it is in broad use by the Euro-

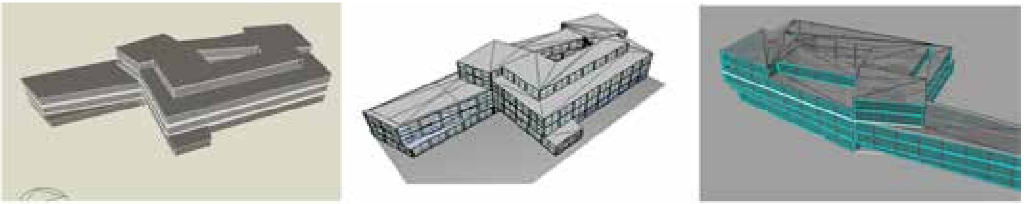


Figure 1
Case study 1 as modeled and imported in the three tools; from left to right, in Design Builder, in Ecotect and DIVA.

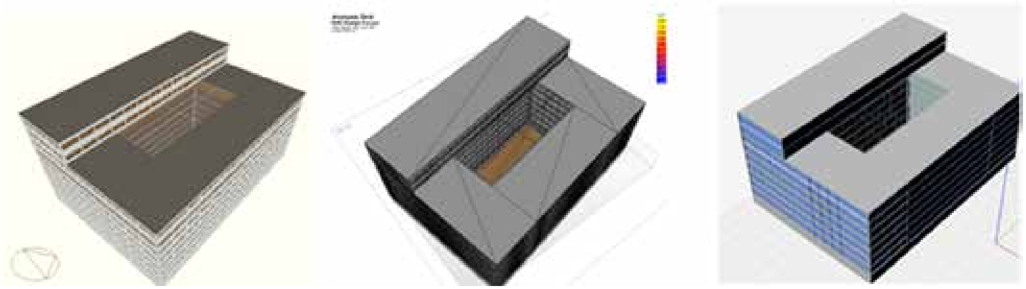


Figure 2
Case study 2 as modeled and imported in the three tools; from left to right, in Design Builder, Ecotect and DIVA.

pean building regulations and most assessment rating systems including BREEAM, in order to provide benchmark values for indoor daylight quality. The specification of daylight quality for the presented case-studies lies beyond the interest of this study. The aim is to evaluate the three packages on the selected criteria and to provide a general framework that can optimally facilitate the selection between the numerous daylight performance calculation tools that are at disposal as open-source or commercial software packages.

Further on, a fourth model was chosen as a separate case study. Its geometry combines circular openings on a circular wall and is part of a project currently under development (Figure 4). The model could not be created in Design Builder and the geometry was imported in Rhinoceros and Ecotect as an .obj file format, which was provided by the architectural team. Importing an appropriate model for daylight calculation via gbXML or connection with SketchUp in Design Builder proved also problematic. As a result, calculation output could be obtained only in Ecotect and DIVA (Figure 5). This last model was further used to monitor the effect of the input parameters, regarding the architectural form as one of them. The tests were performed in DIVA 2.0 and provided an insight on the deviations that should be expected with the change of specific variables. The most important of the variables that were tested and the resulting output under CIE overcast sky for the same IWEC weather file are listed in Table 2.

The above listed results are some of the tests that were carried out in order to specify the influence of the precision settings, the grid density and material properties on the output. Hereby we set as Low precision: ab (ambient bounces) = 2, ad (ambient divisions) = 1000, as (ambient super-samples) = 20, ar (ambient resolution) = 300, aa (ambient accuracy) = 0.1, geometric density =70. High precision: ab (ambient bounces) = 3, ad (ambient divisions) = 2048, as (ambient super-samples) = 20, ar (ambient resolution) = 512, aa (ambient accuracy) = 0.2, geometric density =70.

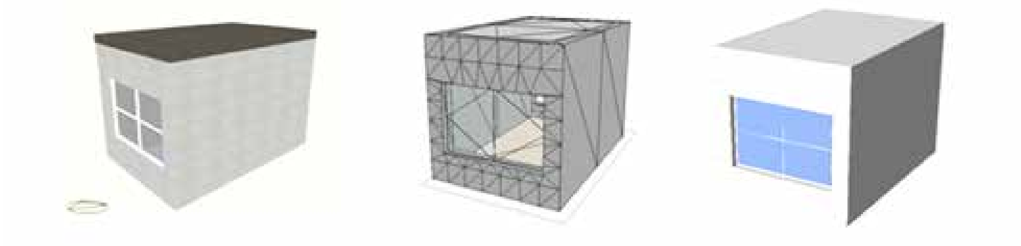


Figure 3
Case study 3 as modeled in the three tools; from left to right, in Design Builder, Ecotect, and DIVA.

Figure 4
Model 4 in Rhinoceros interface: model setup.

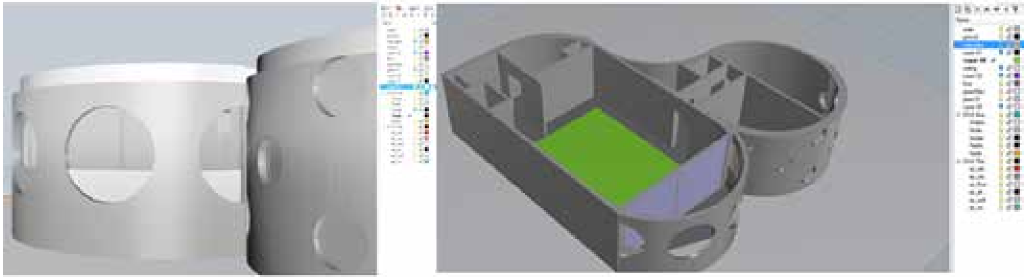
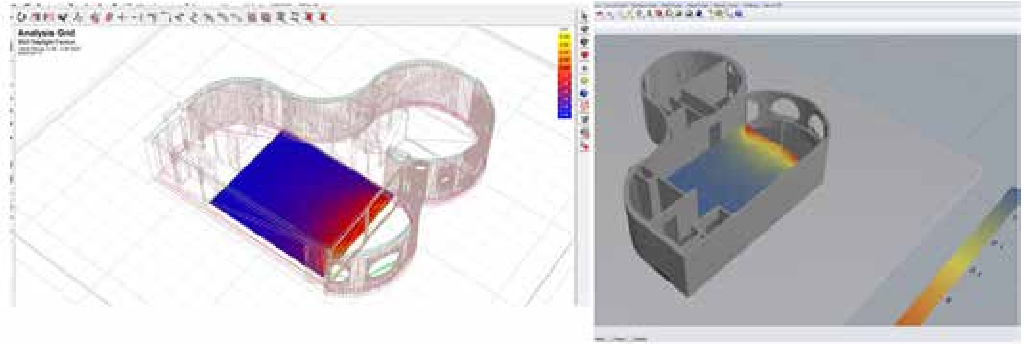


Figure 5
Case study4 as calculated in Ecotect (left) and DIVA (right).



RESULTS

The tests prove that the default precision settings should be considered with skepticism; the minimum number of ambient bounces that could give precise results was 3, whereas a very high precision (4 to 6 ambient bounces) did not considerably change

Table 2
Tests on model 4.

Tests model 4

Test nr.	Material ref. (%)	Precision	Mean D.F(%)
Test 1	Ceiling 0.9, int.wall 0.9, floor 0.5, int/ext. glass tr.0.9	Low, Grid point dist. = 0.1m	1.08
Test 2	Ceiling 0.9, int.wall 0.9, floor 0.5, int/ext. glass tr.0.9	High, Grid point dist. = 0.05m	1.80
Test 3	Ceiling 0.9, int.wall0.9, floor 0.5, int/ext. glass tr.0.9	High, Grid point dist. = 0.1m	1.78
Test 4	Ceiling 0.9, int.wall 0.9, floor 0.5, int. glass tr.0.65, ext. glass tr. 0.9	High, Grid point dist. = 0.1m	0.70
Test 5	Ceiling 0.9, int.wall 0.8, floor 0.2, int/ext. glass tr.0.9	High, Grid point dist. = 0.1m	1.59
Test 6	Ceiling 0.9, int.wall 0.8, floor 0.2, int. glass tr.0.8, ext. glass tr.0.9	High, Grid point dist.= 0.1m	0.98
Test 7	Ceiling 0.8, int.wall 0.8, floor0.4, int.glass tr.0.8, ext. glass tr.0.9	High, Grid point dist.= 0.1m	1.07

Detailed output model 1	Floor area Above threshold(%)	Average DF (%)	Min. DF (%)	Min./Max. Illuminance (lux)
Design Builder v.3.0.0.105				
Ground Floor				
Zone1	61.350	3.916	0.016	1.57/2291.96
Zone2	83.245	2.86	0.5	50.35/964.46
Second Floor				
Zone1	58.898	4.339	0.116	11.62/1970.44
Zone2	48.911	3.248	0.2	20.29/1825.88
- Ecotect 2011 / Radiance				Mean Illum.
Ground Floor	graphically	5.385	graphically	309.6258
Second Floor	presented	4.366	presented	199.1255
- DIVA 2.0				
Ground Floor	62.8	5.5	graphically	217.5
Second Floor	50.7	3.91	presented	158.13

Table 3
Detailed simulation output, model 1.

Output av. DF(%)	Design Builder v.3.0.0.105	Ecotect 2011/ Radiance	DIVA 2.0/ Rhinoceros
Model 1 (15.993 meshes)			
Ground Floor	Zone 1/2 3.916/2.86	5.385	5. 5
Second Floor	Zone 1/2 4.339/3.248	4.366	3.91
Model 2 (23.580 meshes)			
First Floor	2.194	2.2	3.25
Second Floor	2.112	2.34	3.35
Model 3 (136 meshes)	6.378	7.66	7.94
Model 4 (74 meshes)	Not obtained	0.95	1.07

Table 4
Simulation output, average DF, model 1 to 4.

the output. The grid density is important, yet a medium density with a point-to-point distance = 0.1m is enough to provide a reliable output. For double density (point-to-point distance = 0.05m) the effect on the results was at the range of 1.11%, meaning that for models consisted of a large number of surfaces, an extremely dense grid can be safely avoided. The most important material settings are ranked in the following line from the most to the least important: visible transmittance of glazing, reflectivity of the walls, reflectivity of the floor, reflectivity of ceiling.

Tables 3 and 4 present the output from the four case studies as simulated in the three software packages. The differences in the output are indicative of the deviations that can result from the different ability of the software to simulate detailed and complex building forms as well as the differences in precision, even when the input settings appear identical. Moreover, the information that we can obtain with one and only simulation from each program, varies significantly (Table 3). The analysis of the results of test-model 4 have already provided a ranked list on the deviations that we should expect when alterations in the input parameters occur.

As seen in the results from model 1 (15.993 meshes), the setting on the principle of zones does not facilitate the acquisition of direct information on a specific floor. The averages obtained from the zones hereby do not provide clear input for the design team. At the same time, the differences between Ecotect/Radiance and DIVA range between 2 and 10%. In the second model (23.580 meshes) the deviations are bigger; The difference between

Design Builder and Ecotect are below 0,5% for the first floor, yet they are around 10% for the second floor. DIVA gave a daylight factor, by approx. 50% higher if compared to the other two programs. In order to explain the differences, a third simple cubical space was prepared through the same process (136 meshes). The deviation in the output between Ecotect and DIVA was approx. 3,6%, while Design Builder presented by approx. 20% lower values. In the fourth case study we observe that Ecotect and DIVA show a deviation around 10%, whereas no results were obtained in Design Builder due to modeling difficulties as already explained.

The deviations prove, that accuracy is relevant and highly related to program settings, while they are expected to rise when a significant amount of surfaces is computed. Identical settings for the programs are not possible, whereas the 3D form should not be considered identical once imported in different packages.

In relation to interoperability, the workflow can be supported between BIM and non-BIM tools, yet it is important to control the information transfer while exporting a model; 3D geometry can be easily prepared within Design Builder for example, yet the exported .dxf files do not transfer material database information and are normally deprived of the glazed surfaces when imported in Rhinoceros or Ecotect. Additional modeling is then necessary, in order to correct the missing surfaces. An export in multiple files is sometimes advised, in order to facilitate a multi-layered imported model.

The main reason for which Design Builder was used as a base modeler was the fact that most of the energy calculations demand an apart modeling based on energy zones. In such a case, the daylight performance simulation of a building could be performed either on the architectural or the energy 3D model, since both are prepared by the team during the study. In many cases, such as the three first case studies, daylight simulations are possible in both models. Yet, there are cases that the demands of the 3D model exclude one of the two tools, as seen in case study 4.

We attempted to show that the architectural model is of major importance in defining the choice between the available software packages and facilitating the flow of data from the design model to the calculation/analytical model and vice versa. The following criteria can be used as a guideline for the selection of the appropriate BIM tool for the calculation of daylight:

- The type of geometry that the tool is expected to model and calculate; failure in modeling does not necessarily mean failure in performing the simulation. In such a case, the data exchange formats that will be used to import the model are of primary importance. The user has to be informed on the amount of data that can be transferred through the supported file extensions.
- The expected precision in input/output; the choice of the tools should depend on the demanded precision. In any case knowledge of the influence of the input variables on the result is necessary.
- The tolerance of the software in handling different amounts of data; regarding geometry, the total number of surfaces that will be computed has to be taken into consideration. Abstraction is always necessary in order to facilitate the time and precision of a daylight assessment.

CONCLUSIONS

A number of major drawbacks were experienced during the process, especially in relation to computational effort when a significant number of surfaces was involved, regarding a higher probability for errors and longer calculation times. Early stage assessment tools, such as DIVA, can also prove less flexible during later stages of the design. The reason is the lack of detailed simulation output and the inability to set input values directly on the modeled surfaces.

The three software packages should be evaluated differently with regard to the three criteria as set at the beginning of this study. In this frame, Design Builder and DIVA proved that we are not far from the moment when one tool will be used both for the setting of the 3D model and its performative evaluation. Nonetheless, accuracy in the calculation output remains highly dependent on the model setting. For this reason, further examination of the consecutive calculation steps and the relevant files which are produced during simulation (i.e .rad, .tmp), are of great importance, and can explain some of the deviations in the output. On the other hand, Ecotect presented lower flexibility with regard to geometry manipulation, even though it supports detailed material input.

Interoperability between BIM and non-BIM tools remains an issue especially for Design Builder with regard to 3D geometry input and processing, while DIVA/Rhinoceros was experienced as the most flexible during the process. Ecotect facilitated a rather one-sided approach (capable of importing 3D geometries), and proved to be an analytical BIM tool which supports 3D input even when large amounts of surfaces are involved, without serious problems. In conclusion, interoperability as a seamless flow of information is partially supported, while the usability of the architectural model for performance evaluations is heavily dependent on a conscious modeling by the side of the designer, long before the geometry is exported for the calculation, in any interoperable file format.

The hereby presented experiences regarding modeling and simulating geometries of various sizes and complexity, prove that further steps need to be taken towards a better integration of 3D modeling capabilities in the engineering simulation software and vice-versa, especially with regard to the precision of the input values and the operability of the 3D geometry in the BIM environment. The integration of Building Performance Simulation Techniques in the design process, can be facilitated by the selection of a tool that will provide reliable feedback during the early but also the later design phase. Basic guidelines towards such a choice were given during this study, while addressing the issue of accuracy through four different case studies.

Furthermore, the role of the designer is central in facilitating the collaboration of the team and providing an efficient base model that will be bidirectionally used, therefore resulting to a better fusion between the disciplines. In this sense, an answer to the current interoperability problems can be given by a better coordinated design and assessment team, both having a global understanding of the process. Such a team will facilitate the flow of information through the setting of the 3D models, in both BIM and non-BIM tools, when the complexity of the project or the limitations of file formats do not allow for one core model both for design and daylight assessment.

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CAAD Curriculum

How to Teach 'New Tools' in Landscape Architecture in the Digital Overload

Developing emergent design methodologies

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Abstract. *The central theme of the paper is the introduction of hands-on tools showing the integration of information technology within a postgraduate study program (MAS LA) for landscape architects. What has already become a part of the discourse in the field of architecture – generic design – is now also finding more resonance in the context of large-scale landscape architectural design. If one studies the educational backgrounds of landscape architects, however, they often do not match the same standard as those of architects. A solid background in the area of innovative use of information technology, especially computer-assisted design and CAD/CAM construction is only at a preliminary state at most universities. The critical arguments in the choice of the selected medium and the building up of a continuous digital chain stand here in the forefront. The aim is not to improve the quality of the landscape design based on the variety of the applied tools, but rather through the sensible use of the said. Reflections as well as questions of method and theory stand at the forefront of our efforts.*
Keywords. *Design tool development; computational design research and teaching; new design concepts and strategies; parametric and evolutionary design.*

BACKGROUND

At the Department of Architecture of ETH Zurich, both students and researchers have the newest technical equipment and software at their disposal. Optimal networking with professionals in the area of construction as well as CAD/CAM production allow us to offer courses in the curriculum that allow experimentation with the newest techniques and materials. This excellent infrastructure is supplemented with the advanced resources of the Landscape Visualization and Modeling Lab (LVML) founded by the Chair of Professor Girot in cooperation with the PLUS Chair, Planning of Landscape and Urban Systems of Professor Grêt-Regamey (IRL). The LVML is equipped with special devices for large-scale data collection, for example a 3D landscape scanner with 2 km range and a drone. To this end, various software and hardware solutions are combined experimentally in order to investigate new boundaries of perception and illustration of the built environment (Figure 1). Professional partnerships to the developers of software and hardware solutions as well as experts in the areas of landscape and urban planning allow for

Figure 1
Generated Data: Combination of point cloud data from airborne and terrestrial laser scanner.

a hands-on examination and implementation in the various research areas. The difficulty in teaching lies not in the lack of equipment, but rather it is seeing this digital overload as a new challenge in a positive sense.

INTRODUCTION

At present, information technologies are an essential component of design and building construction. Contemporary architecture and large-scale landscape architecture as designed by top offices would not be thinkable without them. Without computer-assisted manufacturing and logistics, modern form language and structural solutions would hardly be realizable. Meanwhile, the software and hardware involved has become so sophisticated that the students' generally increased computer skill levels suffice for an architectural program at a technical university. At the present, a heated discussion on the level of education is taking place especially in the field of landscape architecture within Switzerland. In contrary to architecture offices, practicing landscape architecture offices, especially those in Continental Europe, criticize that university graduates are more and more incapable of understanding and visualizing complex landscape designs. Moreover, the level of expertise in the daily use of digital tools is at a level that is no longer acceptable for an efficiently organized office. In order to close this gap, the MAS LA (Master of Advanced Studies in Landscape Architecture) Program of Professor Christophe Girot was newly conceived in 2009 in terms of content, both methodically as well as didactically. To this end the former design-specific focus was transferred to the learning and use of up-to-date tools.

The MAS LA Set-Up

The course of studies is divided into themed modules, workshops and one concluding synthesis module. The modular structure allows a concentration on individual themes, which can be combined within the framework of an individual project as the concluding thesis module. The main focus of the program is not the acquisition of new software skills but rather the integration of cutting-edge modeling, visualization and presentation technologies as design tools within the field of landscape architecture (Figure 2).

Figure 2
Testing different ways of presenting large scale topographical information by projecting animated information to a CNC milled model.

Each module begins with a phase where new techniques are learned. In this phase, individual exercises are connected to current issues in landscape architecture. The students are encouraged to recognize global as well as local economic and sociological demands and integrate them in their designs using and connecting the learned tools. The achievement lies in the diligent selection and connection of the technology with the environment we live in. The critical debate regarding issues of sustainability in conjunction with large-scale design work in urban landscapes plays an essential role next to the technical aspects. In the second part of the module, participants grapple with complex problems, which will be discussed during a concluding presentation. The sequence of modules start with modeling and CNC production followed by visualization, programming, GIS, applied progamming and ends with media and photography.

We challenge the students to go beyond the boundaries of conventional domains and test the tools in analysis, design, and visualization. The programs and different CAAD/CAAM techniques, which the students have become acquainted with in the different modules, complement each other and should be applied and recombined to explore new design methodologies in their final project (Hagan, 2008). The concluding module of the postgraduate program acts as a test case for the questions or agenda, which have been defined throughout the teaching year.

Parametrism – the Solution for All Problems in Architecture?

Ever since the 11th Architecture Biennale in Venice 2008, is Patrick Schumacher's postulated concept "Parametricism as Style - Parametricist Manifesto" all the rage. For many students, complexity equals quality. The use of parametric tools, i.e. Grasshopper is often seen as the solution to conceptual problems. Our desire is to show students solutions and approaches how they can choose the right tools for the design problem at hand in order to test their ideas efficiently and unconventionally, realize them, as well as also later generate suitable formats for the construction process. Here the learning of specific software does not stand in the forefront but rather the learning of a new way of thinking that understands the tools as integrative design tools (Mitchell, 1990). The sequential structure of the MAS LA program allows the students to deepen their individual interests and test the newly learned work processes on their applicability to professional practice. In terms of content, classical, traditional themes like modeling, visualization, GIS, data acquisition are complemented and leading to a new perspective by working with experimental themes like perception through film photography and programming (Greenberg, 2007; Reas and Fry, 2010) . The goal is to create an overview that shows spatially relevant aspects in landscape structures enabling the students to communicate their future projects within real practice in a professional way. Together with architects, urban planners and city authorities, graduates will be able to illustrate and communicate their design ideas professionally.

DEVELOPMENT OF SPECIALISED TOOLS

What are the tools that adequately serve current landscape architectural trends and how can they be conveyed? The past years have shown us that programming within architecture has become as commonplace as CAD drafting (Wanner, 2010). Within landscape architecture, urban planning but also building construction, for example, parametric designs are often the only solution to dealing with complex form language. To this end we would like to use the computer to realize projects that would not be possible using conventional methods. This requires the further development of digital tools, which allow for the subsequent design and working with the extracted information (Kolarevic, 2003). Programming has the advantage of solving complex tasks, accompanied by the risk of sacrificing the intuitive abilities of a designer. Our goal within the MAS LA program is to reduce the technical hurdles and apprehension towards programming in order to first reach an understanding of its necessity within landscape architecture. (Bohnacker et al. 2009). To reach this goal we have developed specific tools, like the "Sandbox Tool" for the special need of landscape architecture.

How to Influence Topographical Data within a Dynamic Planning Process?

An application influences to a great extent the work processes and therefore the design process. If, for example, at any point the designer is aware of statistics like areas and details regarding the execution of a building, he or she will be able to orient themselves to these numbers and take them into account during the development of a design. If these numbers can only be gained through tedious procedures, they will only be collected at a few points in time and will therefore have a limited influence on the design. Even more so than numbers, visualizations of data can give the designer a feedback as long as these are created dynamically and without much effort. If these presentations contain data on which the design should orient itself, a loop is created ideally from the designer's actions and the presentation of their ramifications.

If the presentation of data influences the designs, in that they are permanently in front of the designer's eyes, the designer must determine how these illustrations look like. The students have to learn how to program in order to maintain a dynamic planning process and in order to control his design.

A further development of digital tools is required, which allows the interaction between design and data. This has to come from the designers themselves, because they have to determine to which presentations they choose to react during the design process.

Taking these problematics into account, the final project of the MAS LA Program shows one example of implementing this thinking within the process. The task focused on the excavation material of a highway tunnel, which had to be 'concealed' within the context of a landscape design. When designing in the conventional sense, our students could not make any concrete statements on the actual cubic meters involved. Only with the integration of an own script they were able to comment at any time on the already built amount of material and thereby

Figure 3
Depthmaps for Terrain(1), Cones(2) and Top View on the Result(3) by student: Chrisine Baumgartner.

maintained absolute control over the impact of design changes.

The Processing script of MAS LA student Christine Baumgartner allows one to manipulate the height of the cones and the terrain lying underneath independently from one another (Bader-Natal, 2010). The heights were saved in two separate depth maps that represent the relative heights through gradations of gray. The height of the cones is always taken relative to the terrain (Figure 3). The sum of the cone volumes can be calculated at any time and in conclusion adapted so that it corresponds with the volume of the excavation material. The simple data modeling of the heights in the form of grayscale images allows for simple data saving and varied processing possibilities. The user can fall back on the entire toolset of image manipulation software in order to influence the height information. Here comes in the Processing script itself tools like brushes for localized work as well as global ones, such as the blur filter. The application allows a view over the area with an orbit camera. Any current condition can be saved with the pressing of a button as an image and the model as a DXF to be used later on for generating a visualization (Figure 4).

Theoretical Programming

Going one step further, we introduced in spring 2013 the first time an intensive 3-day workshop for the MAS LA students called “Theoretical Program-

Figure 4
Using the generated data to automate the visualization process (student: Christine Baumgartner).

Figure 5
MAS LA students using CRC-cards to communicate their set up of the project.

ming". The overall objective of this workshop was the critical reflection of the implementation possibilities of programming, within the real practice as an landscape architect. Out of our experience these projects often fail due to misunderstanding and wrong expectations from both sides.

After the students find an initial foothold in programming with the module "Programming Landscape" this knowledge was deepened in the subsequent module "Applied Programming" where first applications were searched for within known CAD workflows. The results of the past few years, however, have shown us that the students have no problem with creating their own programs only they often do not have the fundamental understanding for their necessity and potential within professional practice.

In order to make a convincing appearance in a professional context, it is necessary to be able to speak the language of the other profession. To this end, we supplement our teaching team with a computer specialist who spans a continuative theoretical background. Programming paradigms of greater scope, for example object-oriented, automata-based and genetic programming will also be presented (Hight, 2008). The students become acquainted with concepts such as spring systems, shape grammar, Lindenmayer systems and agent systems.

At the same time, we take advantage of this short but intensive time together in order to reflect on the module with the students.

The set-up of the workshop was a combination of lectures and role play in the loneliness of a mountain hut in the swiss alps. Within groups of 4, the students were asked to communicate a complex design problematic to a programming consultant. The students have been learning different techniques and methods how to bridge and communicate a design to an IT company (Figure 5).

The result of this experimental workshop was surprisingly positive. The students understood through this playful attempt the problematics and could define potential application fields of programmed solutions in their design. The feed-back of the students pointed out the importance of such reflections and training for the real practice. With the 3 days they learned different techniques, like the usage of "UML", "CRC-cards", "class diagrams", "story board"... to prepare all the desires of the landscape architects, in order to have the IT company programming the software.

The Sandbox Tool

Another aspect that we are investigating at the moment is the simplification of workflows through the unconventional linking of existing software and hardware. What happens when traditional manual techniques are combined with state-of-the-art CAAD/CAAM technologies that are adapted to the workflow? Are the students accepting this simple

Figure 6
In order to understand the complex transformation processes of water landscapes, the student will each be using modelling-sand, realtime scanning stations, and a specially made software to give feedback.

tools as part of their design workflow?

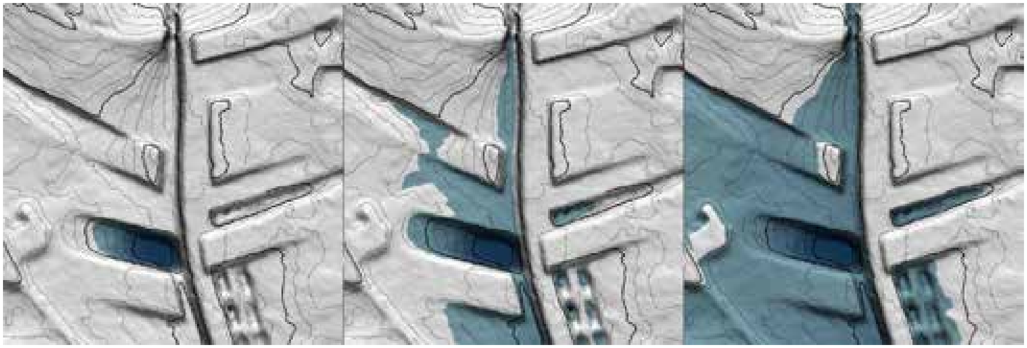
Within the framework of a case study, an existing topography is created in a milled negative model. The students could use this as the formwork, in order to create the same point of departure at any time. The knowledge of this possibilites frees the students to work in a very experimental way. All manual techniques are allowed in the modeling of the designs. If the designer wants to capture a state of the model the student makes two photos from different viewpoints, which are then transferred through photogrammetry into a computer network model where they can be digitally stored and analyzed (Figure 6).

We developed our own software that allows one to generate two-dimensional analyses and visualizations directly. Different analytical methods have been programmed to supply the students analysing their design proposals:

We supply the designer with an elevation map, including a separation of the gradients above and beneath the water table. Additional features include a visualization of the slopes and normalized lighting conditions for all the models (Figure 7).

As a result, the students never work on a computer 3D model but rather focus their work directly on design statements in plan. The 'analog' sand model thereby maintains its significance and be-

Figure 7
LandscapeAnalysis_flodding: 3 Waterlevels composed with Contour Curves from different Layers of the Analysis Tool. Elective Course Students 2012.



comes an interface for analysis and visualization through the associated digital workflow.

According to our observations, the students are very creative when working on the sand model. The milled negative form allows them to return to the original state at any time and they can save any variation of the design with only two photographs. A real physical model cannot offer these qualities. On the other hand, the physical model has clear advantages over a digital one: one is able to work with one's own hands and with any kind of tool imaginable. When one removes material, one is aware of the volume in his or her hands. One inevitably gains a feeling for how much earth is being moved. In addition, a group of students can work on the model simultaneously and be able to discuss from any point of view.

CRITICAL THINKING

While most universities are extremely well-equipped, the students often lack reflection as to the application potential of these digital tools. This often leads to an uninhibited combination of all available tools. The use of generative components like Catia, Rhino, Grashoppper, etc. was only available for experts until around 10 years ago. In the meantime, each student has access to these programs and is able to use the software to a certain degree without any official schooling (Mertens, 2010). The designs become more complex and are often no longer controllable from a certain stage, and the quality suffers under the unfiltered use of the tools. Therefore a rethinking needs to take place within design methodology so that not the learning of specific software stands in the forefront but rather the learning of new ways of thinking that exploit the potential of these tools in integrative design (Leinonen, 2010).

On the other hand, we see the great challenge in the sensible linking of these tools. The concept "Emergent Design Methodologies" spans a top current field, which has the goal of using information technology to support design as well as an analysis, design, and production tool. We see the beginning of the design process already with the gathering of necessary actual data. Through the use of long-range terrestrial scanners, one is able to gather data in the form of point-clouds that can be successively used in combination with aerial photography taken by a drone to create specific and up-to-date contexts for design analysis and the planning process. This first step of the design is especially important for the general understanding and individual advancement of the various design tools. In order to gain this general understanding, students must be given a broad overview of current techniques and research fields in information technology. Through simple and short exercises the manipulation and use of different software modules are to be tested. More in-depth courses und workshops offer the possibility to elaborate the rudimentary knowledge based on the working out of current problems and through the building of full-scale models, in order to be able to test them until the very end in the form of a semester design.

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150 000 – Parametric Control of PET Bottle Structure

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Abstract. *In this paper we describe the pedagogical and methodological approach to a parametric project and workshop for the design of a tower which consists of 150000 PET bottles. The ultimate goal of the project is to actually realize the PET bottle tower; therefore the constraints on the projects are very strict. Additionally, because of the large number of bottles to be used in the design, the problem lends itself well to a parametric approach.*
Keywords. *Pedagogy; garbage architecture; workshop; parametrics; PETower.*

GENERAL FRAMEWORK

This paper is focused on the suitability of parametric design tools for the generation of a tower design that consists of 150000 PET bottles. The tool is taught and used in a 6-day workshop, and is embedded in the context of an experimental collaborative design studio between two faculties of architecture of two different countries.

The problem lends itself well to a parametric approach, as it concerns a composition of many similar units and students need to have control over the total number of components. However, parametric tools may not be sufficient and the only method of designing suitable in all phases of this task. We observed that our students naturally hand-sketched as well. The precedence we could find in Sanguinetti and Abdelmohsen (2007), where the authors successfully describe integration of sketching and parametric modeling in conceptual design task. However, they could also see extreme approaches such as ready sketch design followed by modeling of the same in computer, the use of parametric tool to actually generate the design and the switch back and forth among the two tools. Our report differs in integration of physical material tests into the task and the tested group regarding rather novice students.

Before the workshop we invited expert users (colleague teachers of those programs) of various CAD programs (3DStudio Max, Revit, AutoCAD, ArchiCAD, and Rhino) to create an arbitrary three-dimensional structure of 150000 similar objects. The choice of object and composition were left completely open to the experts (Table 1).

Manipulation of the designed object failed due to the computer capacity in three of four programs. From their feedback we selected Rhino in combination with Grasshopper as the most promising tool in

Table 1
Criteria of choice of the design tool.

	3D studio Max	Revit	Autocad	Rhino
Possibility to generate	yes	yes	design unsatisfactory	yes
Numeric control	yes	no	no	yes
Manipulation of model	impossible	impossible	impossible	yes

the project. Compared to the other programs, it was able to control the high amount of units and also provided numeric control over the design.

We followed the scheme of a traditional architectural design process, where hand drawing comes in the beginning and manufacturing of a model is in the end of the process [1]. Because of the experimental nature of the material and the specific nature of PET bottles it was important that the model was in 1:1 measure. The workshop was open for students at any level of expertise. During the workshop we observed the work flow of the students.

The first two to three days we were teaching Grasshopper. The students discovered that parametric design tools not only generate interesting and cool pictures, but they are also an inevitable part of the design process to support the conceptualization of the design. Last but not least hand drawing played a significant role during the design process.

DESCRIPTION OF THE PROJECT

Both setup of the workshop as a part of the experimental design studio are informed by the context of the project. The project of the experimental design studio is located in Zurich, Switzerland. The city of Zurich organizes a very large festival every three years, called the Zürifäscht. In the current edition, to take place 5-7 July 2013, the festival runs under the theme of recycling. The theme has three subtopics: Recyclata, Recyclodge and Recyctower (PETower). The Recyctower (PETower) is the subject of the experimental design studio [2, 5] in our institution and in the workshop reported in this paper. The task is quite challenging: the tower must be built from recycled PET bottles and contain 150 000 pieces. The structure must be self-standing and lit. It must be built and demolished in no more than three days. For the construction process school children must be involved to assemble the units of the tower. For transportation purpose the units may not be bigger than 2x2x8 meters.

Originally we were contacted to advise on the PETower design. It seemed logical for us that students of architecture would take part on the development of the plans.

PET bottles are not an uncommon material for experimentation in architecture. Several projects exist where PET bottles are used as infill material in facades. The notable EcoARK [3] building utilizes 1.5 million specially fabricated PET bottles. The American architect Michael Reynolds uses waste and PET bottles in his projects [4]. Experimental structures with PET bottles are presented for example by Baerlecken et al. (2012).

METHOD OF TEACHING

First semester: problem exploration

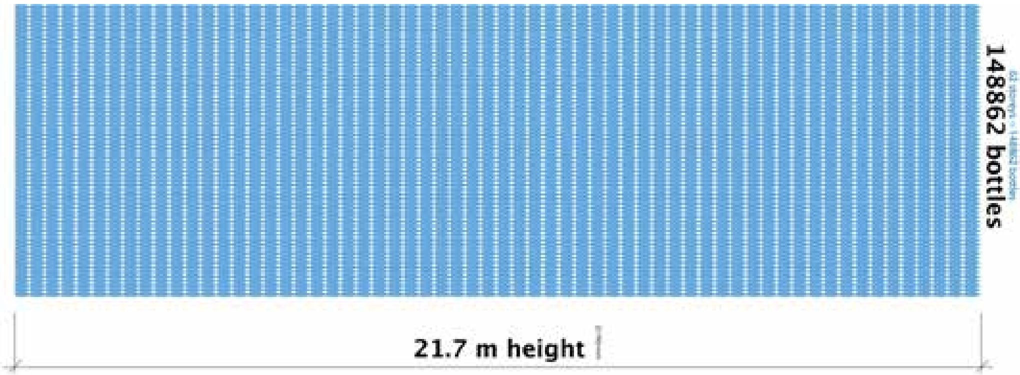
The first semester we led a collaborative design studio between our faculty and the Faculty of Architecture at ETH Zürich. For this project we developed and tested a new software called ColLab sketch, which was implemented in both faculties' media facilities [6]. The advantage of such a collaboration was that part of the team was situated at the site, so that they could supply the team with maps, photographs and sketches of the building place.

The major problem the students faced was visualization of such an amount of units such as 150 000. Figure 1 shows the total number of about 150 000 bottles in a flat area.

In the first semester a number of 3D designs were made with PET bottles starting by coupling single bottles into bunches wrapped in food foil, which worked well but was not of convincing visual quality. Also the stability and reliability of such a structure was doubtful. Some informal tests were done to verify the strength but without reliable results. Finally, having an overview of number of the single bottles within the designed tower was almost impossible, together with the limited design expression. Apart of the communication software which students had to learn we had not recommended any software or design method and we had left their choice open (Figure 2).

The final designs resembled towers, but it could not be proven that they could actually be built.

Figure 1
Visualization of 150 000 PET bottles made by a student.



Second semester: focus on design tools

In the second semester the project was developed at our faculty only, but we had consultation sessions with advisors from the partner university. Different students than from the previous semester took part in this studio. In the first semester we mainly focused on feasibility of the project and did informal material tests and based designs on these findings. The second semester [7] was supported by a 6 day long workshop devoted to information visualization tool lectures and manufacturing. The results were regularly communicated over distance to the advisors in partner faculty and other parties involved in the project.

The scheme of teaching varied in both semesters. In the first semester we allowed the students to design only after analyses were ready: analyses – design – fabrication. In the second semester students could re-use the earlier gained knowledge from their colleagues and shift the start point, so that we could start designing earlier. We also intensified the switch between design and material experience according to the scheme in the table (Table 2).

Most of the time during the semester was devoted to laboratory tests of the PET bottles, where students got the reliable values of the load capacity of bottles and pull capacity of the cap, which we report on at CESB13 conference in Nováková et al. (2013). They also worked on analysing the possibilities of connections using PET materials in a sheet form. We noticed that the designs of the previous semester were limited to regular shapes such as cubes, hexagons or cylinders. In the second semester the students obtained more freedom for their PET bottle designs. Towards the end of the second seminar (during the workshop) we encouraged stu-

Figure 2
Final projects from the first semester.

Activity	Hours	Description
Lecture (film) • Waste land • Wall I • Midway [8]	2	Motivation of the students, primary introduction of topic
Design	4	Initial ideas, concepts, hand sketches
Measurement tests	2	Tests of PET bottles in Civil Engineering (CE) material lab
Design	4	Specifying design strategies
Excursion to PET bottle production plant	8	Learning material generation principles
Design	6	Implementing knowledge from tests and excursion into design
Cap tension tests in CE laboratory	2	Tests of the screw and cap connection, the strength of the screw.
Pressure and behavior tests in CE laboratory	2	Tests on manufactured building blocks in CE laboratory
Workshop - tools	24	Learning of parametric tools
Workshop - prototyping	16	Prototype fabrication
Design	4	Final design + presentation

Table 2
Scheme of activity switch during the semester.

dents with correlating ideas to group and work out one project. Half of the students formed teams of two or three people (Table 3).

During the workshop students took their initial sketches and tried to model them within Rhino. In the first two days they learned basics of grasshopper and understood parametric thinking, on the third day we introduced several ways of generating tower-like objects (Figure 3).

After the initial phase they constructed their virtual models with the data constraints (150 000 bottles, minimum 20 meter height, one component of maximum size 2x2x8 m^3). We found that they could easily change their design towards the initial hand sketch without loosing the awareness of the numbers. Consequently we allowed the students to play with their newly acquainted skill. By allowing them the "play phase" within the teaching hours, the students were more motivated to experiments, deepening their understanding of parametric modeling and got quicker feedback from the teachers. Together with this parametric attitude to the problem, the 4th and 5th day was devoted to building the actual prototypes of the components. Students not only had to

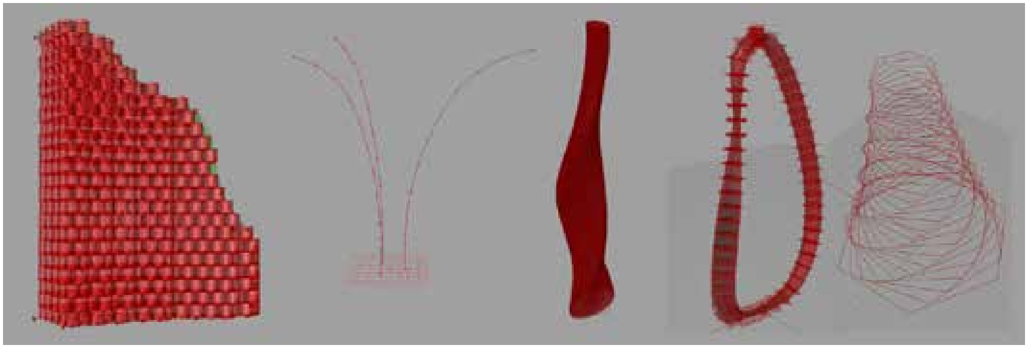


Figure 3
Examples of different possible principles for tower generation. Combination of geometrical shapes and mathematical formulas.

Table 3
Table of project developments.

Students' sketch	Grasshopper model	Physical model of the building unit		Project	Evaluation according to feasibility
Petr	yes	no		PETower	10
Simon	yes	yes	worked		
Lenka	yes	no		Wall	3
Adam	yes	yes	failed	Tripod	9
Petr	yes	yes	failed	Mobius	8
Juraj	yes	no		Lighthouse	7
Sori	no	no		Twisting Tower	6
Ondrej	yes	yes	failed	Atomium	Not feasible
Ivana	no	no		i	Not feasible
Jiri	yes	yes	worked		
Karel	yes	yes	worked	T	2
Honza	yes	no			
Maria	yes	yes	failed	Swiss cross	
Leila	yes	yes	failed		4
David	yes	no		no	Not feasible
Peter	yes	no		Growing Tower	5
Jean	yes	yes	worked	Plasticienne	
Pauline	yes	yes	worked	Plasticienne	1
Vera	yes	no		Pentagon Tower	Not feasible

collect the bottles, but also tried to set the connection between them according to their previous research. We could observe students sitting by the screens and sketching their technical ideas on the paper. This workflow programming-sketching was efficient for them and it proved to be the fastest (Figure 4).

Because the material was experimental, not all assumptions and designs were successful and students had to change their virtual models again according to the real scale component prototypes. Students grouped again in this phase of component generation.

OUTPUT OF THE SECOND SEMESTER

The projects of the first semester did not result in feasible designs which could be actually constructed. We assume that the main reason for this was the lack of expertise in sophisticated CAD tools.

We collected several physical prototypes of PETower building modules together with connection strategies (Figure 5).

In contrast to the first semester we did see thirteen feasible projects in the second semester, which were consequently communicated to several parties in Zurich (municipality, festival organizers, potential

Figure 4
Students programming and sketching designs simultaneously.

Figure 5
Building blocks from the left: circular type (Wall), stick type (Swiss cross, Mobius, Tripod),3D panel (Plasticienne).

sponsors). Three projects were highly realistic and one of them was accepted as a realization project (Figure 6).

CONCLUSION

We collected all sketches, made screenshots of the developing projects and made documentation of the 1:1 models. We observed that students not only computer modeled in the middle phase of designing, but all the time of project development they were sketching even when sitting by the computer. Especially in the phase of moving towards construction we could see simple drawings of connection details or patterns of assembled units. The parametric tool proved to be very important. Some students tried to develop the project with other CAD tools,

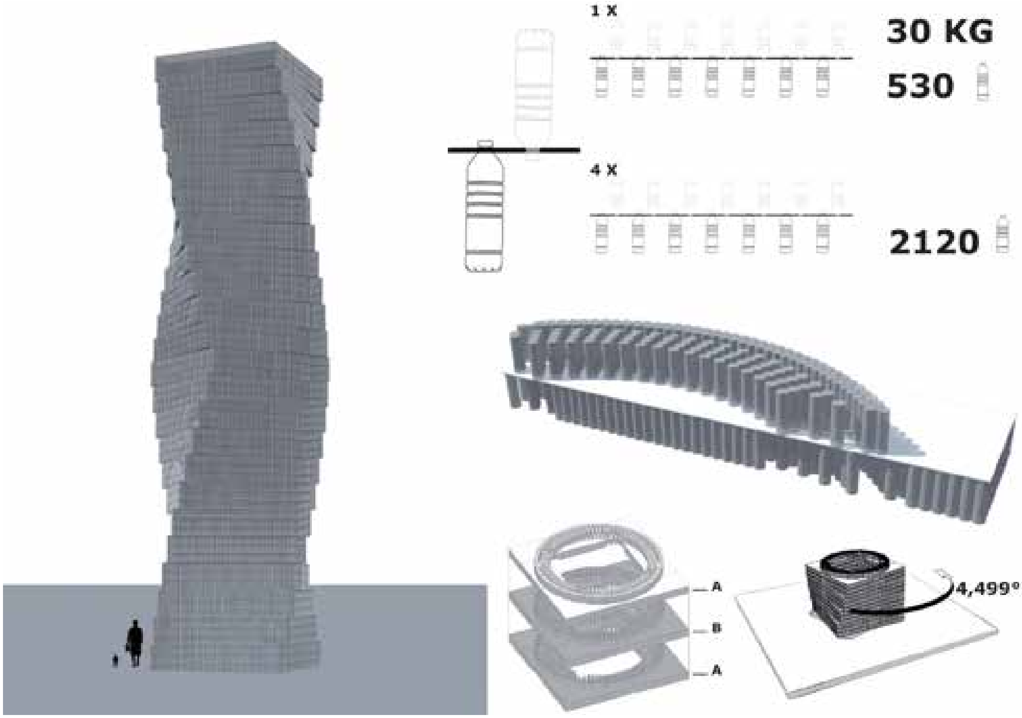


Figure 6
Plasticienne: 23 m high, 148 000 bottles.

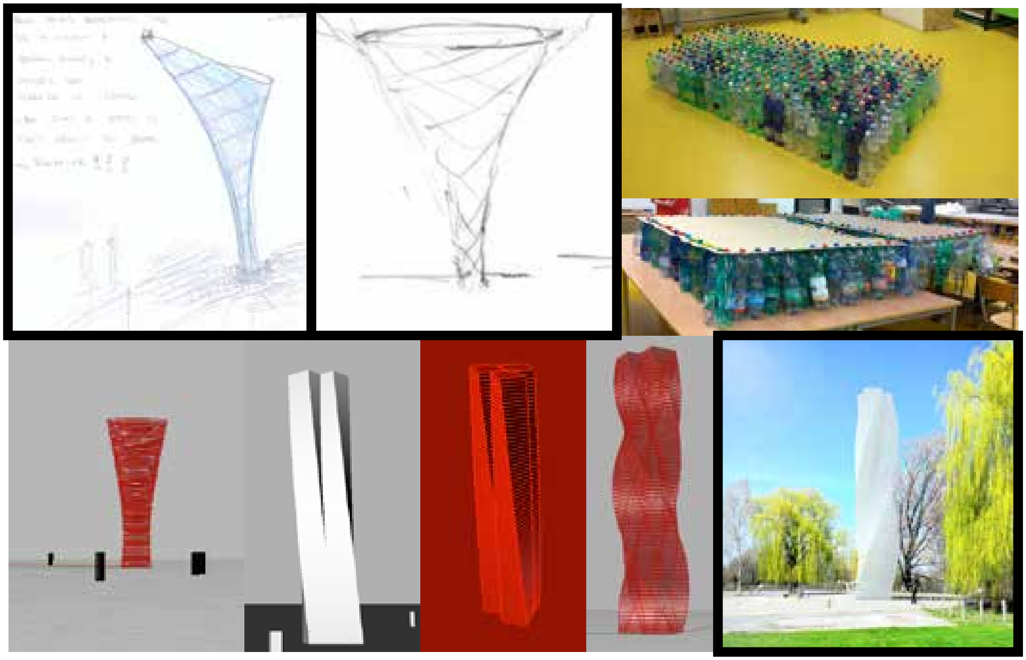


Figure 7
Project development documentation: two initial sketches made by two individuals matched, therefore they decided to cooperate and delivered feasible project.

but failed. Thus they responded very enthusiastically to the parametric tool when they saw how the design remained flexible while keeping also numerical control. As we observed, teams of two or three people were able to deliver results, which fulfilled all conditions of the project, while individuals did not progress beyond trials and failures. For all students it was interesting to see how much the parametric tool enabled them to deal with the real problem. Furthermore they were able to follow their initial hand sketch graphics giving it exact numerical and structural control (Figure 7).

For our experimental design studio and this special task using parametric tools proved to be of critical importance. Also the hand sketch technique seems to be crucial. Parametric tools enabled students to experiment with the tower design, while also keeping control over the various constraints that apply to the project. Exploring various construction methods with PET bottles was on the other hand made on paper and parametric tool turned out to be unsuitable. Hand sketch helped developing initial designs, visualizing partial ideas, generating details and clarifying technical solutions. In general, we feel that it is necessary to introduce similar workshops focused on parametric design in the beginning or middle of the design studio together with the same focus on hand sketch, where we believe in better impact of using of these tools directly in the design studios by project development.

FUTURE WORK

In the next semester of the experimental design studio we shift focus to the design of shelters and small service structures made of PET bottles for the same festival event. We would like to observe the direct impact of using parametric tools on final designs and the role of sketching in this process.

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Identifying Cognitive Operations of Conception Implied in the Uses of Parametric Modeling in Architectural Design: Toward Pedagogical Tools

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Abstract. *The research presented in this paper aims at identifying the cognitive operations implied in the uses of parametric modeling in architectural conception. The uses of parametric modeling in architectural design remain emergent and marginal. How can we teach these practices? The identification of the main cognitive operations of conception allows us to propose accurate pedagogical objectives. This paper presents: the research methods employed, the results achieved and propositions for pedagogical tools.*
Keywords. *Parametric modeling; architectural conception, CAAD curriculum, architecturology.*

INTRODUCTION

Parametric modeling is part of computer aided design process of industrial sectors, such as automobile or aeronautic, for over three decades. For a few years architectural sector has carried out parametric modeling.

Visual programming languages as Grasshopper [1] have certainly something to do with this amazing and growing adoption by architects. Popular among students and professionals, this plug-in of Rhinoceros 3D modeler enables them to build parametric models without any programming or scripting knowledge. However, the uses of parametric modeling in architectural conception remain emergent and marginal.

How parametric modeling is involved in architectural conception process? How architects can be trained to parametric modeling and visual programming language? These two issues must be clarified.

In order to address these questions, we search to identify the characteristics of the cognitive operations of conception implied in the uses of parametric modeling in architectural conception. We interrogate here architectural "conception" that we define as the cognitive aspect of design activity.

This paper presents: the research methods employed, the results achieved and propositions for didactic tools.

METHODOLOGY

Context of the research

Analysis of design practices in architectural contexts (our as well as Kolarevic, Picon or Lindsey ones (Kolarevic, 2005; Lindsey, 2001; Picon, 2010)) shows that parametric modeling is linked to various computer assisted tasks: complex form finding and representation, evaluation, optimization, fabrication, communication, collaboration, etc. We observed that most often parametric modeling actors are not the architects who conceive the projects. Parametric modeling requires expert skills and knowledge that most architects have not yet mastered. How architects could be assisted for parametric modeling during the conception process and how they could be trained are thus crucial questions.

Different studies interrogate the role of parametric modeling in architectural design (Woodbury, 2010; Davis et al., 2011; Chein and Yeh, 2012). The laboratory MAP-maacc interrogates the uses of parametric modeling in architectural conception thanks to a cognitive approach. This paper synthesizes researches carried out in the context of a PhD in this laboratory. The purposes of these researches were to describe the use of parametric modeling in the architectural sector in order to identify the cognitive operations of conception involved. This knowledge on the cognitive operations of conception allows developing methods and didactics tools.

Corpus

In order to identify cognitive operations of conception implied in the uses of parametric modeling in architectural conception, observations and interviews were performed. We have analyzed conception practices carried out: in professional contexts (at Foster and Partners, Hugh Dutton Architectes and Ateliers Jean Nouvel among others); and in design studios of schools of architecture at Vienne (at the Universitat die Angewandte) and Paris (at the Ecole Nationale supérieure de Paris Malaquais, Ecole Nationale Supérieure d'Architecture de la Ville et des Territoires among others).

Methodology

In the cognitive science field, very few approaches interrogate the conception and especially the transformation of the conceived artifacts (conception is mostly interrogated as activity). Architecturology is a scientific field of research on Architecture that allows it (Boudon et al., 2000). This research field provides a scientific language for describing cognitive operations of architectural conception by which giving measurements to an artifact. These operations are described in terms of *dimensions*, *references* and *relevances*. *Dimensions* refer to the measurement supports, i.e. to what the measurement is given. *References* refer to the viewpoint from which measurement is given. *Relevances* refer to how measurement is given. The *dimensioning* operation is an elementary operation of conception that consists in linking a *dimension* to a *reference* through a *relevance* (Boudon et al., 2000, p.154).

From these architecturological concepts, we have analyzed our corpus and identified several cognitive operations of conception by using the method of Applied Architecturology developed by Lecourtois (2011).

MAIN COGNITIVE OPERATION IDENTIFIED

Distinction between parametric model conception and architectural conception

Before presenting our architecturalogical research methods, we need to explain how we proposed to interrogated the use of parametric modeling in architectural conception. We didn't interrogate parametric modeling as assistance for a design, but as a conception activity in itself. We proposed to use the architecturalogical apparel to interrogate the architectural conception as well as the conception of parametric model. Does the conception of parametric model can be distinguished of the architectural conception? How these two conception process exchange or influence each other? These are the issues we interrogated in this research.

Elementary operations of conception

Our analysis shows that the elementary operations of conception built by architecturology can describe the conception of a parametric model. "Slicing", "referencing" and "dimensioning" are operations allowing the description of the conception of parametric models as activity of attribution of measurements.

The "slicing" operation is the activity led by someone when he decides to conceive a specific part of an object. For example, when a conceiver decides to model a grid of circles and to drive the diameter of the circles thanks to their proximity to a specific point, he mentally does a "slicing" that focuses the attribution of measurement on the diameters of the circles.

The "dimensioning" is the operation by which a conceiver gives a measure to an object thanks to an activity linking a relevance and a dimension. For example, in the precedent case of the grid of circles, when the conceiver decides to measure the circles thanks to their distance to a point, he is doing a "dimensioning". We have developed more specifically this operation in a previous article (de Boissieu et al., 2011).

The "referencing" operation is implemented by a conceiver when he chooses a context or a family of relevancies to attribute measures. For example, still in the case of the grid of circles, if the conceiver decides to link the measure of the circles in an exact equality with the distance of each circle to the specific point, then he sets up the attribution of measurement in a specific mental world (a geometric one) which proceeds from "referencing".

If the analysis shows that these elementary operations of conception are useful to interrogate parametric models conception, the analysis also shows where the uses of parametric modelling in architectural conception overflow these elementary operations of conception.

A case of conception described thanks to the "elementary operations" of conception

Let's take a specific example from a student's work, in purpose to describe the cognitive operations that can be observed. The project "Topographies" has been developed by Aurea Rodriguez, Pablo Gancedo, Samya Pelloquin and Mathias Saboya in the course "Architecture Paramétrique" led by Nadir Tazdait and Francesco Cingolani in 2012 at the Ecole Nationale Supérieure d'Architecture Ville et Territoire. This project is an urban installation in the Parisian suburb "Cité des 3000". A topography is created to animate the public space and to allow different uses: parking, circulation, playing ground, sitting place, etc. (Figure 1).

In the parametric model developed in this project a surface is used as a reference to create a grid of points (Figure 2). Each of these points is moved in the Z direction in function of its distance to a set of curves. The more the points of the grid are closed to one curve of the set, smaller is the Z translation. All the Z translations are bounded by a maximum and a minimum values defined by the students.

The surface on which the point's grid is created corresponds to the easement of the public parking on which the "topography" is supposed to lean. The set of curves that controls the Z translations represents the main circulations ways and some parking places. The minimum Z translation value is zero to allow an easy access from the "topography" to the street. The maximum Z translation value is defined not to mask the view from the first floor apartments of the surrounding buildings.

// the "dimensioning" of the original grid points

- within an architectural conception:
  When the students have decided to conceive their topography on the parking easement, they have done a "slicing" operation linked with a "dimensioning" one: the measure of the "topography" fit with the existent public space.
- within the conception of a parametric model :
  It is also observed in the conception of the parametric model: to dimension the grid of point in Grasshopper (Figure 2) a surface on Rhinoceros is used as an easement for code.

// the "dimensioning" of the Z translations

- within an architectural conception:
  The students conceive the "topography" project to allow different uses such as : circulation, playing ground, parking spaces: the topography of the project is dimensioned from the wanted functionalities of the project. For that, the slopes of the topography are conceived to: allow an easy walk, separate a parking place from a playing ground zone, etc.
- within the conception of a parametric model :

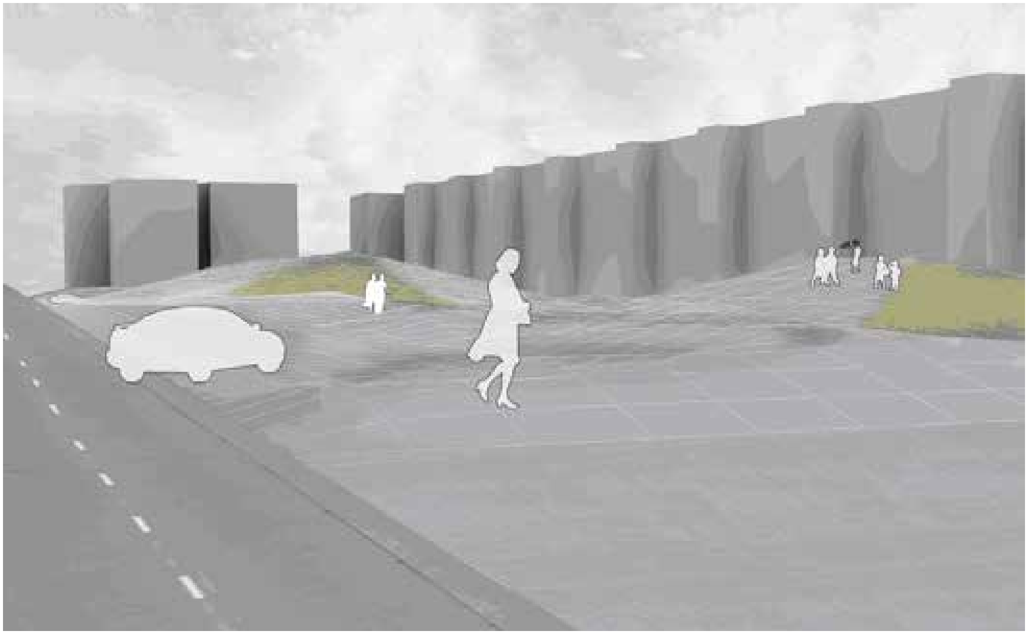


Figure 1
« Topographies » picture of the project from the students Aurea Rodriguez, Pablo Gancedo, Samya Pelloquin and Mathias Saboya (Ecole Nationale Supérieure d'Architecture de la Ville et des Territoires, Nadir Tazdait, 2012).

> The Z translations of the grid points are linked to a set of curves. The curves are linked to the main ways observed in the existing public place and to the wanted parking places. The Z altitude of each point is dimensioned to be close to zero in proximity of a set of curves.

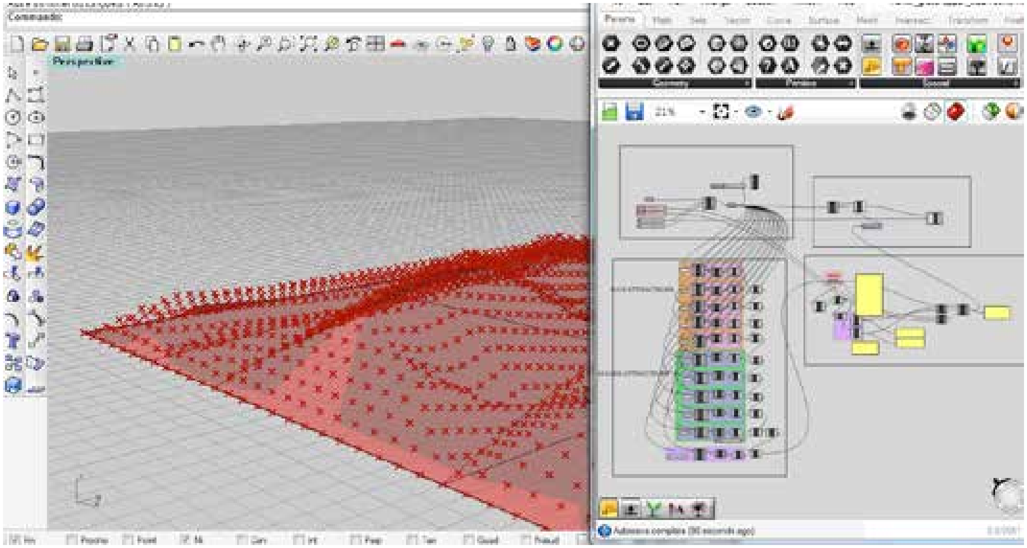
In these different operations we can observe that we can distinguish operations of conception of parametric model and operations of architectural conception. But we can also observe that these distinctions show how intricate and porous they are. The links and exchanges built between these two kinds of activity (conceiving the architecture and conceiving a parametric model) are interrogated in our research in terms of third operations: the "pragmatic operations".

Not an operation of architectural conception either an operation of parametric model conception …

"Pragmatic operation": In her research, Samia Ben Rajeb had identified some operations implied in collaborative conception that not give directly measurement to an object. She formalized these operations as "pragmatic" one (Ben Rajeb, 2012, p.281). The following operations that seem to be implicated in the uses of parametric modelling in architectural conception are kind of pragmatic operations.

Operations of collaboration: In our analysis, we observed the occurrence of two *pragmatic operations* identified by Ben Rajeb: the operation of "**pooling**" and the operation of "**interpretation**". The "pooling" operation is an operation by which collaborators with different point of view and different expertises, share information in purpose to attribute measurements to an object (Ben Rajeb, 2012 p.286). This operation operates in the use of parametric modelling in architectural conception when different collaborators (for example architects and model manager or parametric design experts, etc) share knowledge about the projects (the architectural intentions, the necessity or potentiality of a paramet-

Figure 2
« Topographies » picture of the parametric model.



ric modeller, etc) to link the architectural conception and the parametric model conception. The "pooling" is an operation by which a conceiver translate and negotiate his meaning in purpose to communicate it for a collaborator.

The operation of "**interpretation**" is an operation by which a conceiver gives a personal meaning to their collaborators discourse and information (Ben Rajeb, 2012 p.285). It operates for example when an expert of parametric modelling interprets the discourse on architectural intention in purpose to define constraints or parameters of a parametric model. The "interpretation" is an operation by which a conceiver gives a personal meaning to information shared by a collaborator.

Pooling and **interpretation** are operations aim at building some "référenciel opératif commun" (de Terssac and Chabaud, 1990) that we can observe in shared relevancies and references.

Elaboration of cognitive representation of the tools: From the case analysis, an operation of elaboration of cognitive representation of the tools can be identified. These representations are based on interpretations of a specific tool (its potentiality, difficulty, etc.). It operates in parametric modelling among other when an architect builds an understanding of the potentiality of the modeller to propose a specific way to conceive a space. It can be observed for example in the imaginary built by Frank O. Gehry about the parametric modeler CATIA (Lindsey, 2001).

Operation of translation in parametric geometry: The **translation in parametric geometry** is a pragmatic operation specifically observed in the uses of parametric modelling in architectural conception. By this operation, a conceiver shift from one system to another (from an architectural system to a geometric and parametric one and reverse). For example, in the case "Topography" previously described, we can observe a translation from an architectural relevance "answer with different slopes to the wanted uses" to a relevance for the parametric model "directly associate the Z positions of the grid points to a set of curves that position in the space the wanted uses".

Hugh Whitehead and some of the actors of the SMG and ARD teams at Foster and Partners talk about such an activity of "interpretation" (Whitehead, 2009; Freiberger, 2010). We use the term "translate" in this research because if interpretation is needed (as giving a personal meaning [2]) it seems that this last activity implies to transpose from one system to another one [3].

These different operations show that if activities of architectural conception and activities of parametric model conception can be distinguished for the analysis, they are also porous and intricate thanks to different third operations. These operations are, to some extent, already proposed by architecturology such as operation of collaboration (with the operations of "pooling" and "interpretation") and the interpretation of the conceiver about the tool. But there is also specific operation to the uses of parametric modelling in architectural conception: the transposition of relevance or reference from a system to another one (the operation of translation in parametric geometry).

Logical operations and knowledge

Logical operations: Logical operations of induction and verification can also be observed in the uses of parametric modelling in architectural conception. Some induction operations appear when a conceiver establishes few cases of his object to then induce some rules or a system able to define these different cases. An operation of verification appears when a conceiver tests his parametric model in different particular cases. By induction, the conceiver thinks from the instances to the parametric model. In verification, the conceiver thinks from the parametric model to the instance.

Knowledge for parametric modelling in architectural conception: The elementary operations of conception as well as the pragmatic operations described need some specific knowledge to be implemented. The analysis of the different operations helps us to define this needed knowledge. As part of this knowledge we can list among others: architectural knowledge; geometric and mathematical knowledge; knowledge in computer science and more precisely propagation based system (Aish and Woodbury, 2005; Woodbury, 2010).

TOWARD PEDAGOGICAL TOOLS

The results of the research presented above, led us to propose didactics tools for assisting architects to parametric design. These didactic tools are: accurate pedagogical objectives for parametric modeling training and training resources.

General training objectives

Parametric modelers are constantly updated: new versions are regularly proposed as well as new plug-in. Furthermore, research is active in this field: new explorations are regularly published. Practices of parametric modeling seem to be in a demanding situation: fundamental knowledge is needed (as we formalized above), as well as a continuous update of the knowledge and practice of the field.

To answer to this specificity, a training of parametric modeling in architectural conception should focus on :

- fundamental knowledge,
- learning abilities in this specific field,
- relevant didactic tools that can be used to improve specific issues even when the training is over.

General skills that training in parametric modeling should aim to develop are:

- abstraction (logical and geometrical);
- organization and anticipation;
- participation to a community of amateurs, a network linked to the students interest, work as a team;
- curiosity, self-motivated.

Pedagogical objectives

Thanks to the results previously built on cognitive operations implied, we can also define specific requested behavior and know-how that are, for the moment, specifics to parametric modeling experienced experts. As Hugh Whitehead says « *I think the changes are more about attitudes than about technology and that comes with experience* » (Whitehead in Kocaturk and Medjdoub, 2011, p.238).

For each cognitive operation previously identified in the use of parametric modeling in architec-

Table 1
Pedagogical objectives linked to cognitive operations.

To implement these operations:	**A learner should be able to :**
slicing operation	Decompose an intention of parametric model in terms of logical and geometrical chain of dependencies
dimensioning operation	Decompose an intention of parametric model with proper and specific relevancies, especially linked to his architectural intentions
logical operation of **verification**	Test the viability of his parametric model in extremum instances of his solutions domain
logical operation of **induction**	Define general rules from particular sketches
operation of **translation in parametric geometry**	Interpret an intention in terms of propagation systems, hierarchy of the dependencies and geometrical constraints
operations of **collaboration** (**interpretation** and **pooling**)	Give a personal meaning to a collaborator discourses, find information specific to a new problem

tural conception, we can propose some pedagogical objectives (Table 1).

Didactics resources

We defined then a pedagogical framework of web resources that architects can exploit during design process and for training. This framework includes a general knowledge support and a specific knowledge support for the visual programming language Grasshopper. The general knowledge support [2] provides resources on geometry, computer graphics and more broadly on applications of computer sciences to architectural design.

The Grasshopper resources are gathered into a library of samples presented with images of possible produced shapes, a describing text with keywords and obviously the corresponding *.ghx code [4]. This library is proposed as mediation for the use of Woodbury's patterns (Woodbury, 2010) by non-expert in parametric modeling.

CONCLUSION

This paper presents some of the main result we obtain on the identification of cognitive operations implied in the uses of parametric modeling in architectural conception. We have interrogated parametric modeling as an activity of conception in itself (conception of parametric models). Our analysis shows that elementary operations of conception proposed by architecturology (*slicing, dimensioning, referencing*) are accurate to describe the conception of parametric models. We identify as well some porosity between conception of parametric modeling and architectural conception. These porosities are allowed by third operations: operations of collaboration (*interpretation* and *pooling*), an elaboration of a cognitive representation of tools and a specific operation of parametric modeling (*translation in parametric modeling*).

Thanks to the identification of these characteristics of the uses of parametric modeling in architectural conception, we proposed accurate: -general training objectives, -pedagogical objectives and -didactics resources.

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Continuous Oscillations

A didactic for augmenting architectural design education with computational design techniques via integrative feedback loops

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Abstract. *We present and discuss a didactic for augmenting architectural design education with computational design techniques via integrative feedback loops and show examples of student projects. Our goal is to embed new technical skills into existing design abilities as quickly as possible, in order to enable our students to exploit and explore the extended capabilities of digital design techniques within the framework of architectural design projects. We instigate a process of continuous mutual feedback between different fields: on the one hand between technique-based exercises and design-related steps, and on the other hand between the digital and the physical. Through oscillation and feedback, the newly learned skills are directly interwoven with the existing ones. Special emphasis is put on the illuminative effects of transitions between different media and on issues of fabrication.*
Keywords. *Design curriculum; tools; shape studies.*

GENERAL AIM: EXTENDED POSSIBILITIES

Digital tools extend the scope of possible design solutions. With them, designers can formulate, control and construct solutions to design problems that would otherwise be either too time-consuming or impossible to conceive and handle. This is mostly due to the difficulty of the geometry involved (such as intersections between polyhedral or curved elements), or its complexity, its number of elements. It is important for us that our students can understand and handle the new possibilities in such a way that they are free to choose which solution they see as the most appropriate, regardless of matters of complexity, style or form.

DESIGNING WITH NEW TOOLS: THREE TYPES OF OSCILLATIONS

We therefore introduce two things simultaneously: designs tasks that challenge the borders of non-digital possibilities, and together with them digital tools that allow students to cross those borders and extend their own scope of abilities. Thus, the students access new aspects of the design problem from an understanding of new tool possibilities and vice versa. Their learning oscillates between designing and tool acquisition.

Additionally, we always task students with the production of physical models. Building those models becomes possible through the new digi-

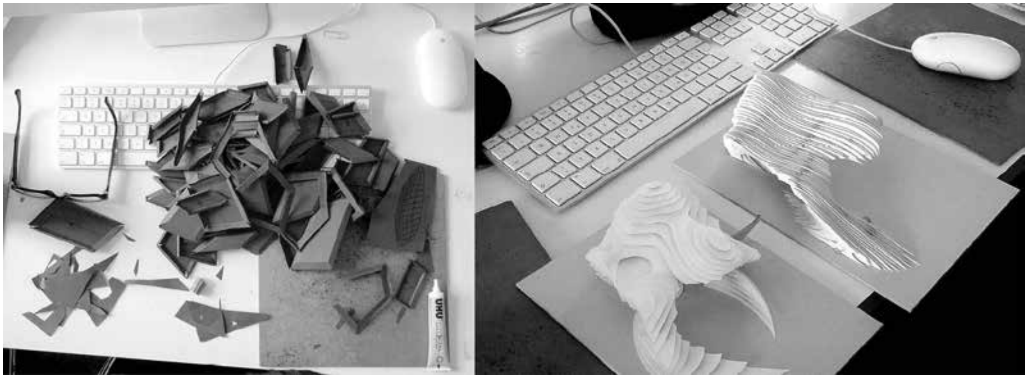


Figure 1
Study models in progress adjacent to Rhino Workstations.

tal design tools. The models are not just for the final presentations, but also sketch models that as early as possible transfer into the physical what was sketched digitally (Figure 1). This has three main reasons: Firstly, physical models in ‚real‘ 3D space are much more comprehensible and expose a design's qualities much better than digital models projected onto a 2D screen. Secondly, even simple sketch models already start to hint at production challenges that become much more important when building in 1:1. Today, we think, it is rather easy to be seduced by the possibilities of digital tools into conceiving projects that then run into problems when they come to be realized. Early model-making makes the students address such possible difficulties literally at first hand. Thirdly, the transition from digital to physical sometimes comes with mistakes, especially when students try out certain techniques for the first time, experimenting with production tools and materials. Such mistakes can very often be made productive because the ‚wrong‘ or ‚failed‘ translations can unintentionally show new aspects of the original that were difficult or even impossible to see there. So a second oscillation occurs between the digital and the physical.

A third oscillation is attempted between the little, simple design tasks in the course and the larger and longer design projects students undertake in parallel courses. The tasks we set are aimed to equip students with techniques that also serve their larger projects, and we invite students to bring problems from their more complex projects into the course so that they can be discussed and solutions be found.

DESIGN COURSE STRUCTURE AND DESIGN TASK SEQUENCE

We have structured our design course in three steps. In each step, a pavilion has to be designed and presented in two-dimensional representations as well as in physical models. Before the precise design task is set, we introduce various CAD tools. The design tasks themselves then include certain requirements, conditions and restrictions which invite if not require employing the tools just introduced.

In each step, the physical models use less material, but the parts are more laborious to assemble.

Where digital models can be made up of geometries that are continuous and as large as designers desire, physical models and - even more so - real buildings have to be assembled from components. The ever faster development of large scale 3D printers only partially remedies this, because the printers mostly rely on very fine strata which, when viewed closely, again dissolve the continuities.

As software we use Rhino in conjunction with its Grasshopper Plug-In. Rhino is in the process of becoming the lingua franca for architectural 3D modeling, dito with Grasshopper for simple programming of such software.

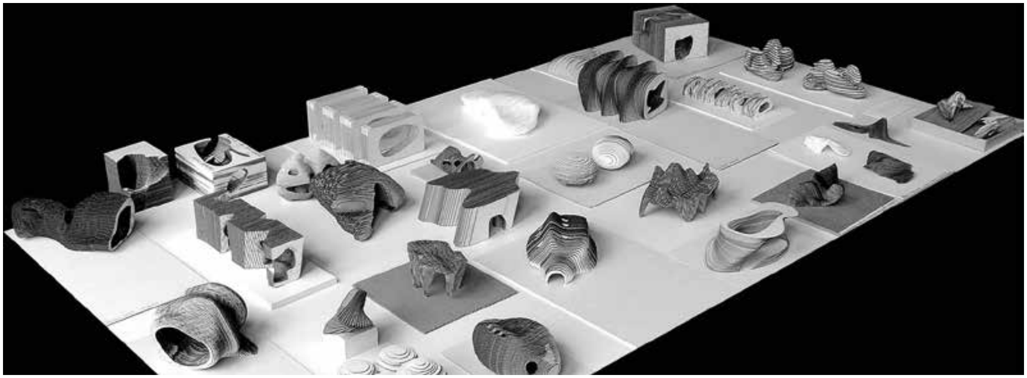


Figure 2
Stratified pavilion models.

MILIEU FOR WORKING AND STUDYING

We chose simple pavilion as topic for the design exercises in order to bridge the gap between exercises dealing with the technical capabilities of the software and the challenges of architectural design - context, construction, spatial program, functionality. Pavilions do incorporate the latter, but to a degree that can be rather freely chosen by the students, so that there remains space for play and experimentation with the former. We strive to create a playground-like milieu where playfulness, experimentation and risk-taking are common, so that students dare to - so to speak - flex the new-found muscles they have been equipped with (meaning the new software tools). We encourage the students to attempts in which they are at first likely to fail. The learning effect, and the sense of self-satisfaction on the students' side, to us appears higher this way. For the students to be able to easily move conceptually we aim to create a ground that is both slippery and padded so that they can move swiftly and fall easily - but soft.

Our intention is that students transfer the new possibilities explored through the new skills acquired onto other design projects they are or will be working on; projects with more numerous and realistic requirements in terms of spatial program, constructability, functionality and relationship to urban and socio-economic contexts. Our more simple pavilion designs are intended to serve as test cases, where investigations can be faster and more radical within a protected experimental realm isolated from various restrictions.

STEP 1: CURVED FREEFORM SURFACES AND STRATIFIED MODELS

The first pavilion has to have various seating possibilities inside as well as outside, and its roof has to be accessible. It has to be a continuous form, not an assembly of components: all functional and circulation elements have to be synthesized and integrated into one coherent shape. Its physical model has to be built from different strata cut manually or with a laser-cutter (Figures 2 and 3).

We introduce free-form modeling tools in two steps: at first solids are manipulated through their control points for quick but imprecise shape exploration. Thereafter, surfaces are created from control curves - a more laborious but much more precise and intentional design method. Sculptural and functional aspects of the created surfaces are discussed, and the relationships between their aesthetical qualities as objects ore public sculptures and their usability as architecture. Categories like 'furniture', 'house', 'wall', 'roof', 'stair', 'ramp' that appeared fixed become fluent. A solution space for architectural design that was compartmentalized becomes a continuum. The prevalence of purely horizontal surfaces in architecture is questioned and uses for inclined planes found and discussed.

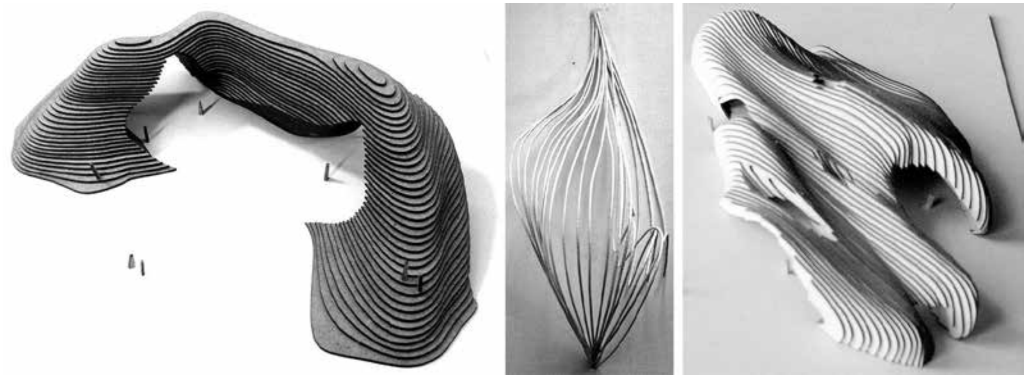


Figure 3
Stratified pavilion models.

The digital designs are then sectioned into strata, stacked vertically or side by side. The stratification becomes a design theme in itself: how are the strata orientated, and how thick are they, i.e. how many of them are there ? Students explore different stratifications, even un-parallel ones, experimenting with radial and curved arrangements and strata that have trapezoid instead of rectangular sections (Figure 4).

Students experience that the stratification can be seen either as an unwelcome tainting of the seductively perfect digital model, or as a means of structuring the endlessly pliable; making it more disciplined and taut.

Very often, the resulting designs play with the difference between outside and inside shape and exhibit rather thick intermediate spaces. Furthermore, students enjoy the possibilities of doubly curved surfaces.

We encourage students to see occasional transition difficulties between digital and physical model-making as 'happy accidents' and exploit those as welcome design ideas (Figure 5).

STEP 2: INTERSECTING SPACES AND DEVELOPABLE SURFACES

The second pavilion has to be the result of three intersecting shapes. The different source shapes have to be recognizable in the resultant exterior shape and create different spatial regions inside. These regions - as opposed to separate rooms - have to be associated with different functions. The hull surface has to be developable and built as a shell as thin as

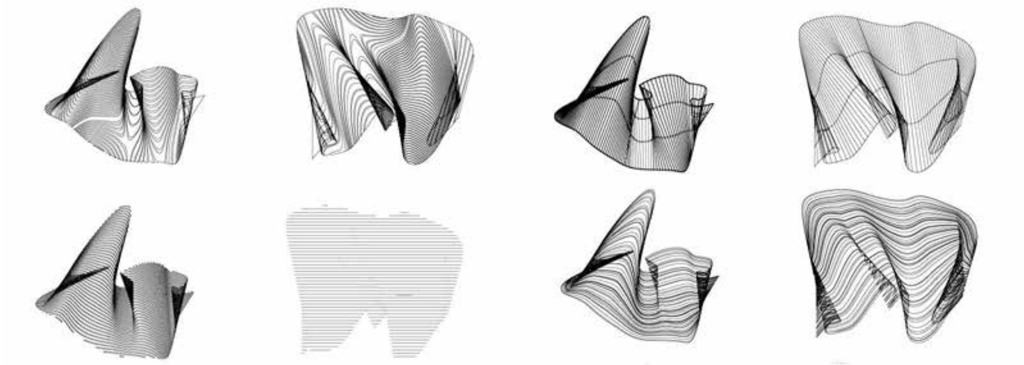
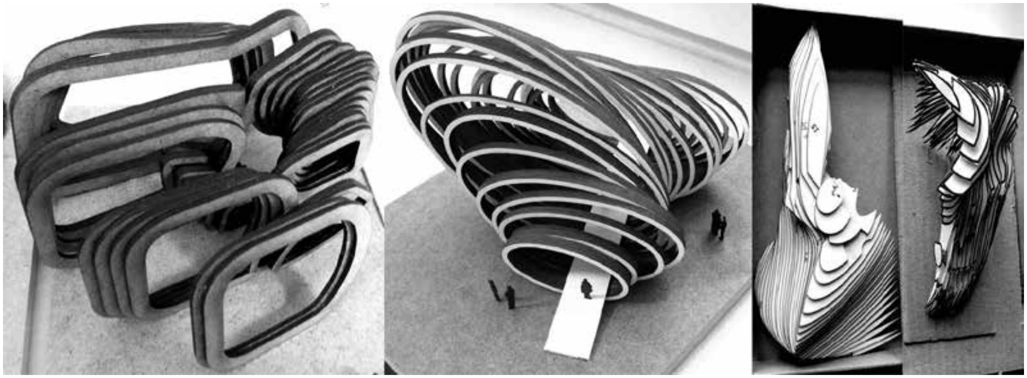


Figure 4
Stratification Studies.

Figure 5
'Happy Accidents': Transition Difficulties between digital and physical exploited as design ideas.



possible. Apart from the technical possibilities of intersecting objects, means of dividing space into different areas other than primitive walls are explored. Boundaries between different regions are discussed as ambiguous. They do not stem from separating elements which are inserted into an already existing shell but result from the mere shape of a complex space. In other words: continuous spaces are differentiated via widening and contraction, embodied in the seams of the different intersections. Furthermore, the possibilities of 'negative' spaces are explored; spaces that are created through boolean difference.

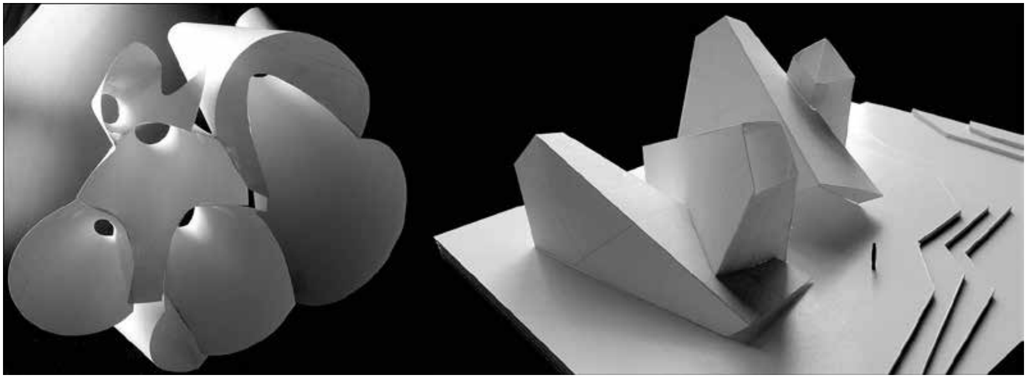
The 'Unroll' command is introduced together with boolean commands for intersecting and splitting shapes and separating and exploring the resulting pieces.

The formal and sculptural freedom experienced in the first task is restricted, but the designs more tightly coupled with the production possibilities. Much less material is used, and its fabrication does not rely on the availability of laser printers (Figures 6, 7 and 8). The interplay between (almost) unrestricted digital form-making and the reduced possibilities of physical production are experienced and discussed.

Special emphasis is put on how additional stability can be achieved in the physical models by having the intersected parts support one another.

Again, we aim to let the students welcome the parameters of physical production into the design as informative factors rather seeing them as obstacles.

Figure 6
Intersecting spaces and developable surfaces pavilion models.



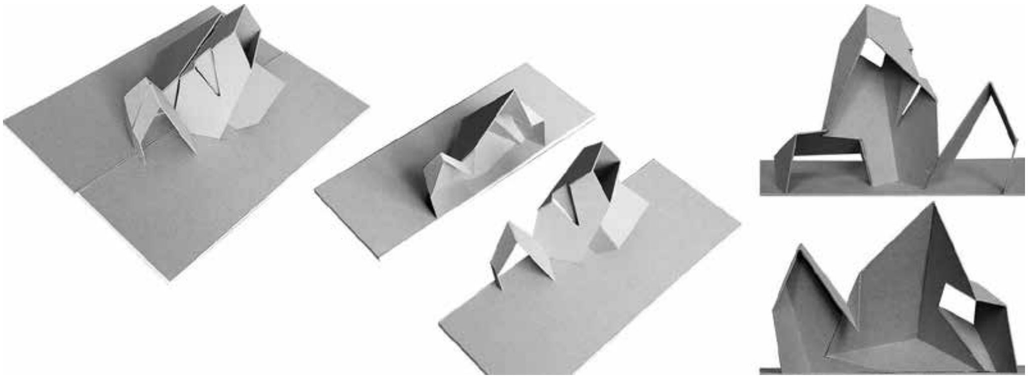


Figure 7
Intersecting spaces pavilion sectional models.

STEP 3: COMPLEX ROOF AND DISSOLVED HULL

The third pavilion is more of a roof, i.e. for an archeological excavation. It has to be a single surface that changes from convex to concave at least once. In order to fabricate it, using Grasshopper the surface is populated with a three-dimensional pattern in such a way that it is divided into multiple developable surfaces. The population pattern has to include holes so that the resulting populated surface becomes porous (Figure 9).

We employ a simple and well-known grasshopper definition that divides a surface into a rectangular grid and maps a given geometry onto the individual cells. The parameters in the definition's most simple form are the surface, the geometry to be mapped, the number of u and v separations and the height of the projections. Occasionally, we extend the definition with more parameters, varying the height or leaving the uniform division of the surface behind more complex patterns.

The de-materialization from Step 1 to Step 2 is further continued as the resulting surface is perforated so that its holes are larger than its solid parts. The geometrical restraints that were introduced from Step 1 to Step 2 are removed again. The formal freedom from in Step 1 is synthesized with the construction capabilities from Step 2.

Students study the effects of the geometry of the population modules and the population system

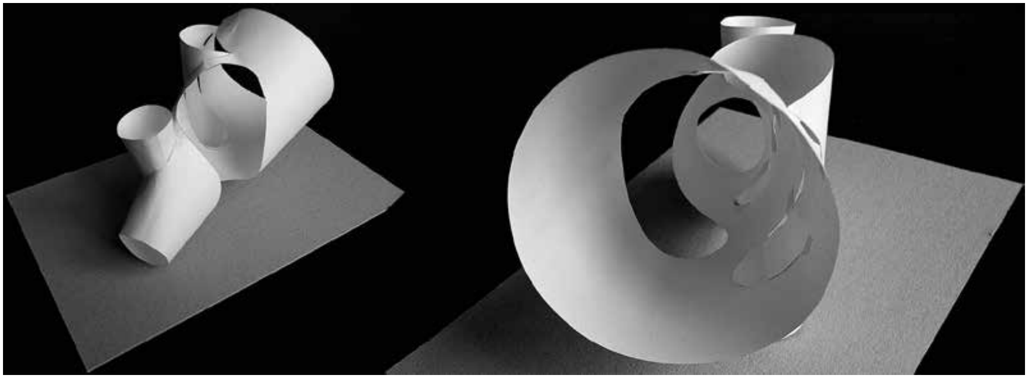
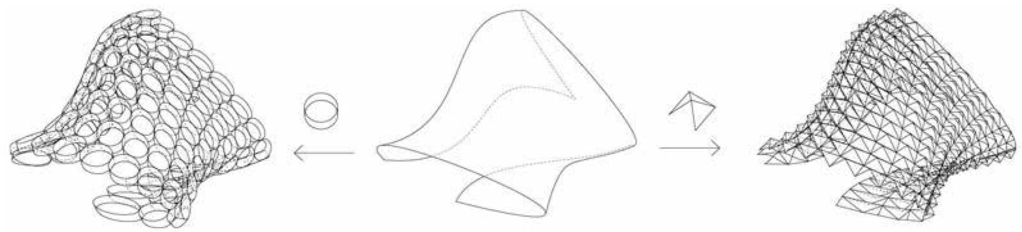


Figure 8
Intersecting spaces and developable surfaces pavilion models.

Figure 9
Three-dimensional pattern population variations.



on the original surface and explore the difficulties and possibilities in fabricating modules and surface (Figures 10 and 11). Certain combinations of surface curvature and mapping height easily create self-intersections. The definition does not check for those - this would have been to difficult to implement within our course structure.

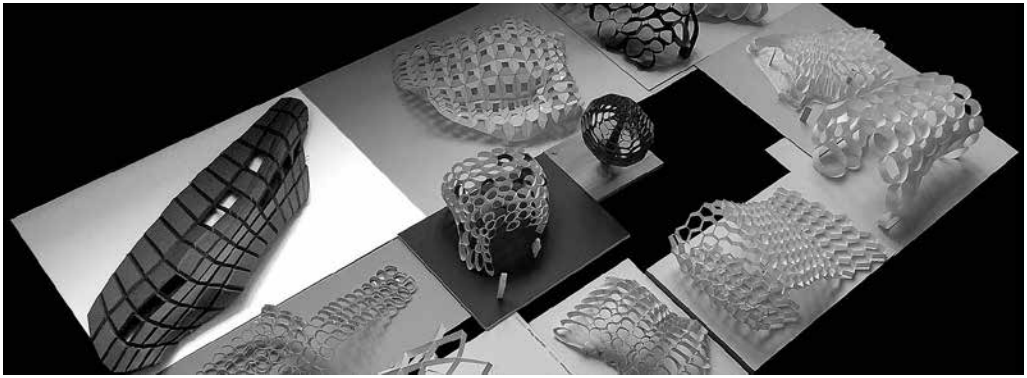
The possibilities of customized mass-production - already hinted at in design step 1 - are explored and discussed.

In order to fabricate and assemble the numerous parts that make up the surfaces, the students, after having worked individually in tasks 1 and 2, now form groups of 3-4. So in addition to the CAD techniques, design possibilities and fabrication methods, teamwork is experimented with: who does what, in which sequence are steps undertaken, how are communal decisions reached ? Such teamwork has always been important in a discipline where, like with composers but unlike visual artists, designers are not builders. It is, though, becoming ever more important as the growing number of design tools and fabrication methods increases the number of specialists while decreasing the percentage share of existing skills that any individual can have - thereby raising the number of specialists and therefore the need for shared work and communication of goals, intentions and ideas.

CONCLUSION AND OUTLOOK

In order to extend existing design skills, we introduce technical possibilities of CAD software with conceptual and geometrical design tasks. We attempt 3 oscillations: between technical tools and design possibilities, between digital and physical models, and between simple architectural designs within the design course and the larger design projects students work on in parallel. These repeated movements between different modes of working in time weave numerous conceptual strands that be-

Figure 10
Complex roof and dissolved hull pavilion models.



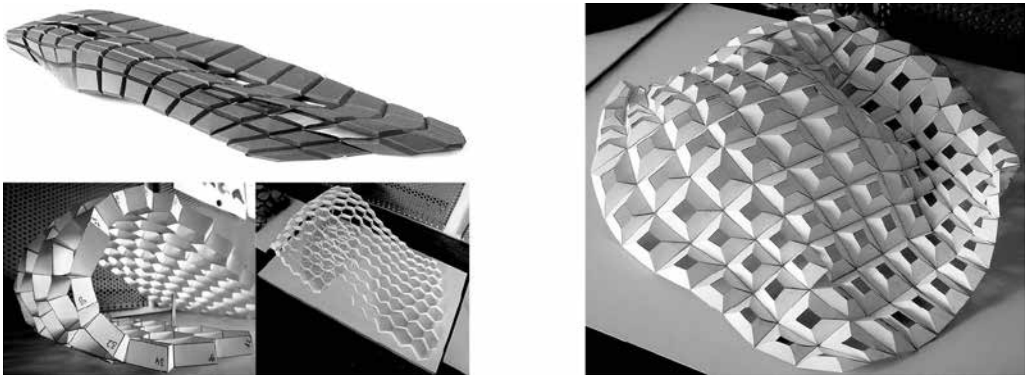


Figure 11
Complex roof and dissolved hull pavilion models.

gin to tie different conceptual regions into a whole.

In the future, we aim to intensify this weaving, especially of the work done within the design course and the work done outside of it, so that the new territories opened up for designing architecture can be traversed more naturally.

Computation/Performance

Problematizing education_ integrating computational methods in relationship to 'performance' within a new undergraduate curriculum

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Abstract. *Setting up a completely new architectural academic curriculum for a brand-new school of architecture. Elaborating, critical space within the new curriculum for the teaching and learning of 'digital-technologies' (DT) through the integration of them with its core subjects, rather than understanding the teaching/learning of such technologies as an add-on set of skills that comes a posteriori. How to articulate the potential of the 'Computational-Architect' as a professional capable of being a productive agent within society; that is, capable of adding Value. The nature of such is what it's at stake here, if we want to avoid to become or be reduced to mere providers of services.*
Keywords. *Computation; performance; ecology; code; maker.*

INTEGRATING COMPUTATION_PROBLEMATIZING EDUCATION

To have the opportunity of setting up a completely new architectural academic curriculum for a brand-new school of architecture is an extremely exciting challenge that does not appear often.

Within this task, even more exciting for the discussion at place here, is the project of intentionally dedicating, as well as elaborating, critical space within the new curriculum for the teaching and learning of 'digital-technologies' (DT) through the integration of them with its core subjects, rather than understanding the teaching/learning of such technologies as an add-on set of skills that comes a posteriori.

Besides summarizing the above mentioned experience, this paper tries to also evaluate the outcome of the implementation of such DT after its 5 years of incipient existence (2008-2013). This period is equivalent to getting a Bachelor's degree, and in consequence, the level of produced work is of a: Basic Level. However, and maybe precisely, it is considered especially relevant as is the result of establishing DT's basic-structural disciplinary seeds at the very foundation of the development of a practice.

The paper will try to evaluate the failures and successes, and the reasons behind those. Examples of work accompany the text.

NUMERIC CULTURE

The question of DT's autonomy -or not- within architectural making, together with the capacity of this technology to form an independent corpus of work and discourse by itself, is key.

In the light of the European higher education area as prescribed by European policies, together with the practice of an architect being a regulated one by the Government (in its final form of professional associations needed to practice/perform/sign), it is more than legitimate to affirm that there is no actual spot allocated for DT (computation+fabrication) in an undergraduate/eec curriculum today. And hence it is also legitimate to question why that is.

Since the inception of DT into architecture during the 90s, DT have come into play as a radically disruptive form of knowledge for the architectural discipline. Over the years, there has been an increasing acceptance of them on every front. However, the myriad of courses of all sorts of formats that have appeared since then, still place the teaching/learning of DT at the 'End' of an architectural academic degree (post-graduate levels) or at most, as a specialization (end of bachelor or workshop).

This paper aims at posing critical questions as well as describing a critical reflection on the education of the 'digital-native'-architect.

A clear bias is placed on an Education Model as a platform for research (as a focus of investment in education as much as a true cultural and productive innovation), over a model based on teaching as a mere form of transfer of previously accumulated knowledge.

Implementing DT undergraduate program 2008-2013 implied settling down the very foundations of a new kind of culture. What's important is the creation of a 'not-analogue' kind of culture, but a numeric one (Figure 1).

PART 01_COMPUTATION / EDUCATION

'I think everybody in this country should learn how to program a computer because it teaches you how to think' (Steve Jobs, The Lost interview).

This academic curriculum aims at establishing the proper intellectual environment for active engagement in building-up a set of skills and techniques based on the embracement of Digital Technologies as the relevant tooling apparatus for current and future generations of architects.

Considering the current socio-economic European current context; i.e. the complete re-organization of the global-economy and the new emerging cultural paradigm slowly appearing in the midst of a crisis that particularly affects spatial practices, the matter becomes:

How to articulate the potential of the 'Computational-Architect' as a professional capable of being a productive agent within society; that is, capable of adding Value. The nature of such is what it's at stake here, if we want to avoid to become or be reduced to mere providers of services.

The underlying guiding principle in structuring this DT-CV, has been from its beginning, a very simple urge to convey to students the relevance of moving on from their initial (immediately gratifying) use of DT as representational tools, into generative methodologies.

Our goal has been to add the necessary skills that allow for both the conception and control of higher geometrical orders as well as software interoperability. But above all, to convey: Why all this matters, i.e., to be able to fully communicate Why it's important to expand the limits of 'conventional' CAD concepts and 'user-friendly' interfaces that, nevertheless, do nothing much more than constrain architectural language through predetermined architectural elements. In short, the aim of this project has been to create the intellectual foundations for a design culture based on algorithmic thinking and digital fabrication (Figure 2).

Epistemology

This alone, and perhaps simply said, implies nonetheless an enormous and unparalleled epistemological change. It definitely is the most radical shift of mentality that has occurred since Modernism and its Post-s... i.e., the fact that within an associative design framework, students are forced to address the problem of how to design and fabricate architectural components that are 'Programmed' rather than 'Drawn'.

Probably the most obvious of the proven consequences of introducing DT in undergraduate archi-

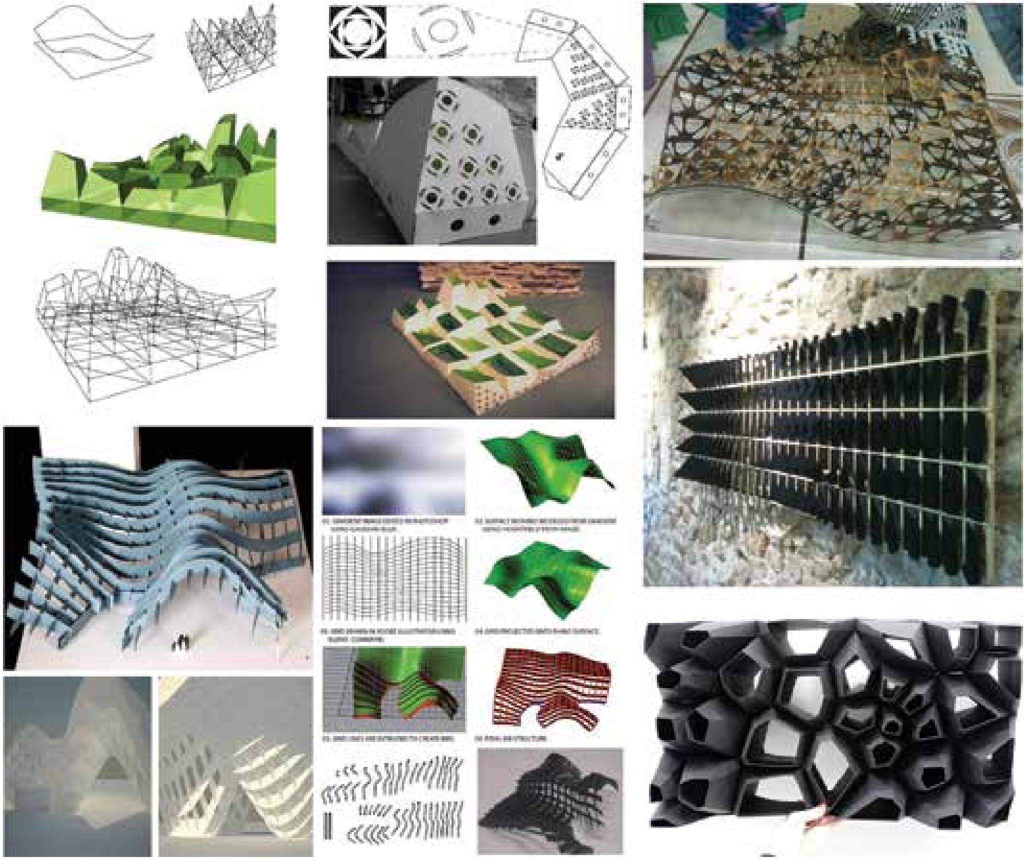

Figure 1
NuDL_Digital Technologies_First Year.

tecture school (programming- fabrication, whether hard-coded or graphic-scripting), are the questions and discussions on 'process-driven' design that inevitably and immediately arise. Even if 'rule-based' design systems have been mainstream for decades already in some design contexts even in analogue form (Eisenman) , there still exists an extremely high resistance (even fear) towards the reformulation of design Authorship and what constitutes such notion today.

This might explain why implementing DT has been (in our specific context) reasonably achievable and successful (by being accepted and willing to implement it) in almost every area of the academic CV

Figure 2
NuDL_Fellowship.

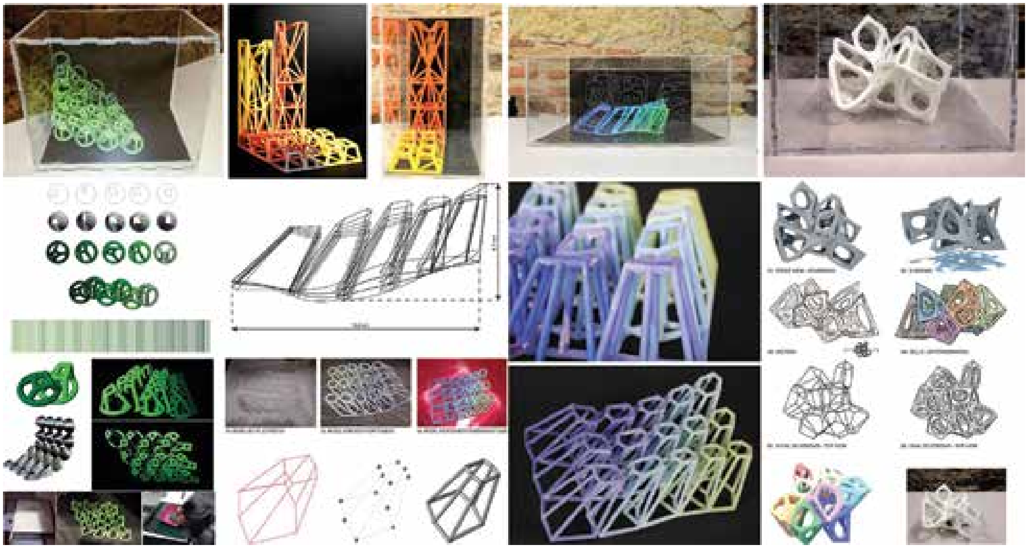

Figure 3
NuDL_Digital Technologies02_First Year.

but design studio, which is the area where we have found most resistance from. Before jumping into obvious criticisms however, this fact might have a very simple explanation. One that lies at the core of the problematics that emerge out of the profound shift in architecture-making due to the impact of DT (Figure 3).

Instrument vs Method

If structure, construction and representation classes have welcome DT's corpus of knowledge in collaboration with their own, it is primarily because parametric modeling, programming and digital fabrication are mainly valued as 'Instrument' and not 'Method'. To be more accurate, as an instrument for improving: a) workflow, b) variable input/output and, c) delivery of precise geometric data to be taken to digital fabrication and/or performance analysis.

Nonetheless, this fact alone we argue, merely constitutes a slight automation device of otherwise traditional and conventional design procedures, bypassing the truly essential foundation of parametric and algorithmic thought.

The degree of control necessary to develop an initial intuitive hunch by means of the hard-core rigor that computational tools entail is such, that the designer must be skilled first, and above all, in the 'Logic of Design' of highly complex systems that comprise -geometric, algebraic and logical- relationships.

As educators, a two-fold task presents ahead of us; on the one side, to keep up with the fast rate development of DT's as intrinsic to themselves (Computer Science), and on the next, to focus on the relationship with the corresponding culture of 'use' within Design Practices. What is key, is how to trigger the combination of 'Intuition and Logic' both of 'Ideas and Skills' in one single but multidimensional dynamic ensemble.

Experience over the past 5-years has proved that prejudices as to what architectural design 'is' or 'ought to be' still exist. And the introduction of programming and digital fabrication within architecture´s education has still to overcome an extensive set of deep-rooted classical values. Most surprisingly is the fact however, that these prejudices do not always come from some of the more established layers of the profession (as perhaps expected),

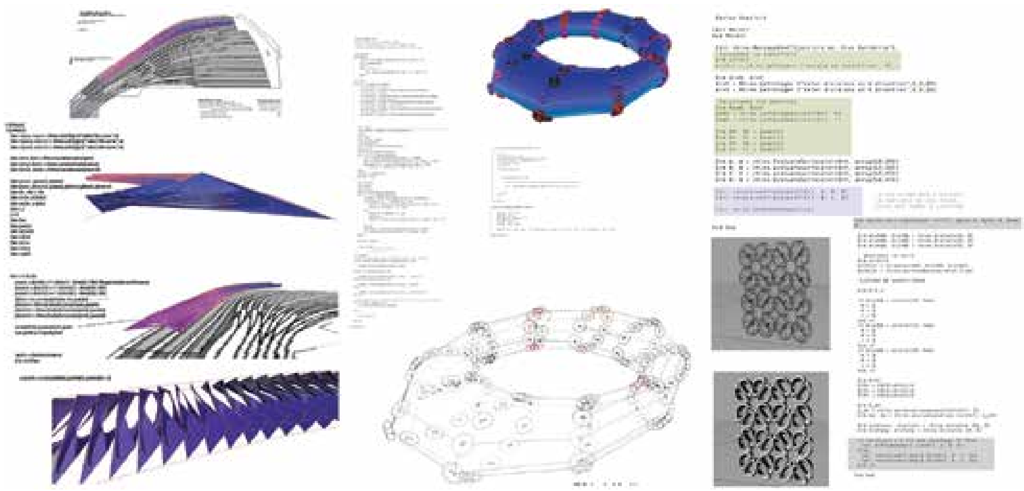

Figure 4
*NuDL_Scripting_First Year_*
Professsors: Carlos Barrera, Adolfo Nadal.

but also, from the collection of 'a-priori assumptions' that young candidates arrive at architecture school with . . . not only about the discipline, but also in respect to the the digital, and the radical change that is involved in making a highly 'strict' use of what they otherwise have known to be 'playful' devices.

At an institutional level and in contrast with the type of architectural education's resistant attitude we have tried to convey, a couple of non-architectural examples are here worthy of noting. Such projects are born out of a true honest belief in the capacities of computer code and the new epistemological paradigm opened-up by DT. Those are: Code.org [1] in the USA, and the recent enterprise taken on board by Code Club [2] in the United Kingdom (an afterschool voluntary initiative that aims at teaching computer programming to 10 year-old kids).

'At age 10-11 (on average) children have the necessary numeracy, literacy and logic skills to learn the concepts of coding' .... 'Some might argue that they have these skills even earlier than that. To be blunt, ICT lessons today mainly consist of learning Microsoft Office. Are we raising a nation of secretaries? I sincerely hope not. It's insulting to children to think they can't handle something more creative, inspiring and powerful than an Excel spreadsheet' (Code.org Co-founder Claire Sutcliffe (Geere, 2012))

Such initiatives deserve our deepest respect indeed. It is most admirable to have achieved for computer code to surpass the 'geek' community in order to become a Country's policy for children's education; a generation, let's not forget, that will still take 10 years approximately to get to Undergraduate Schooling.

And this is fact alone proves, that architecture schools should stop worrying about how to preserve traditional disciplinary knowledge modes and cease to have a conservative attitude in order to fully (and rapidly!) embrace programming and fabrication, as well as the rest of the vast array of DT.

Because, to put it very simply: These are our New Standards. And as such, this is the responsibility of architecture education today (Figure 4).

PART 02_COMPUTATION / PERFORMANCE

Even if the expected resulting final work to be delivered by an 'Architect ' remains being a physical structure (a built design), it has indeed become more than clear that the contemporary architectural model we all participate in (every agent in the design-to-construction process), is an evolving one

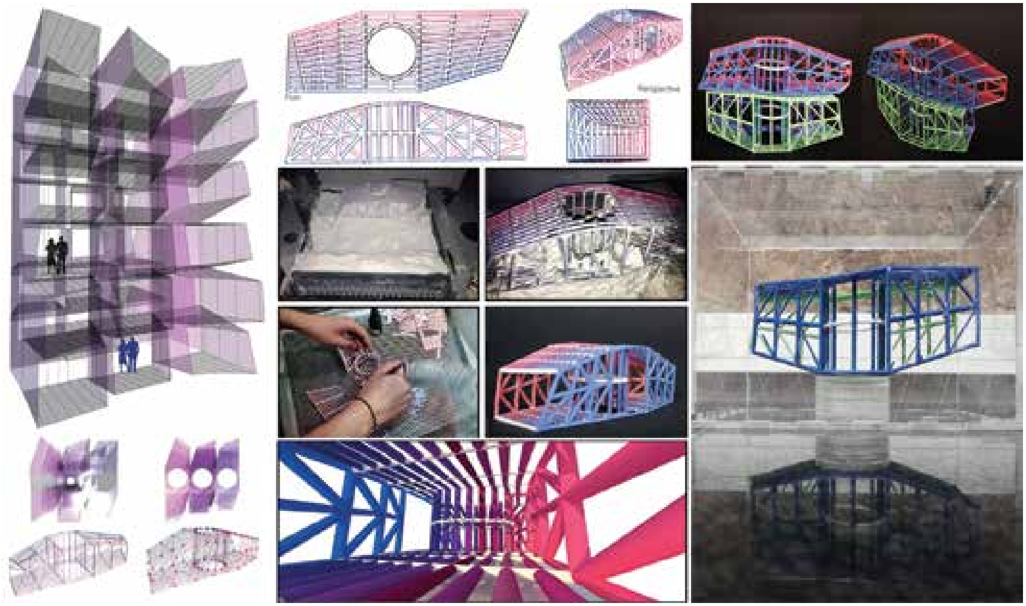

Figure 5
NuDL_Digital Design_First Year.

that has become as much cybernetic as material.

Computation has given the designer an unprecedented degree of Control over the complete spectrum of design-build processes. As a design tool, it is capable of dynamically defining the global coordinates of a generic continuum, to then yield up to a specific (intentional) configuration. The criteria for evaluating which single instance is most suited for a particular design problem, is what drives us to the notion of Performance.

As a measure of the direct output of a driven process, performance is usually conceptualized as the increase-or-decrease in efficiency of such process. Although computation has been incorporated into the discipline of architecture, it has been mainly used for two main tasks: a) to generate complex geometries that intensify the function of the Formal; or, b) instrumentalised as mere optimization device without exploiting its ontological/cultural potential beyond technocracy.

Our mission has been to articulate a digital expertise for the 21C Architect whose practice is of a clear distinction from the one of the Engineer. Hence, computation in relation to performance is evaluated here with an explicit criticism towards statistical and self-referential efficiency models as sole alibis or testing-modes of resulting prototypes.

In biology, epigenetics studies how environmental factors affect genetic function (genotype). Similarly, 'rule-based' design processes have at their starting point the definition of a robust 'genotype' that can be subsequently refined according to feedback-loops that incorporate further information external to itself.

Ecology is not sustainability. In an effort to reconsider the Holistic 'intelligence' formed by the whole complex set of spatial components (digital, physical, material, economic, atmospheric, etc.), computational design ought to develop a model capable of strategically, tactically and synergetically relate to its environment. The utilization of Code as design method acquires full meaning only if it dynamicaly integrates the affects of the material context in which it develops (Figure 5).

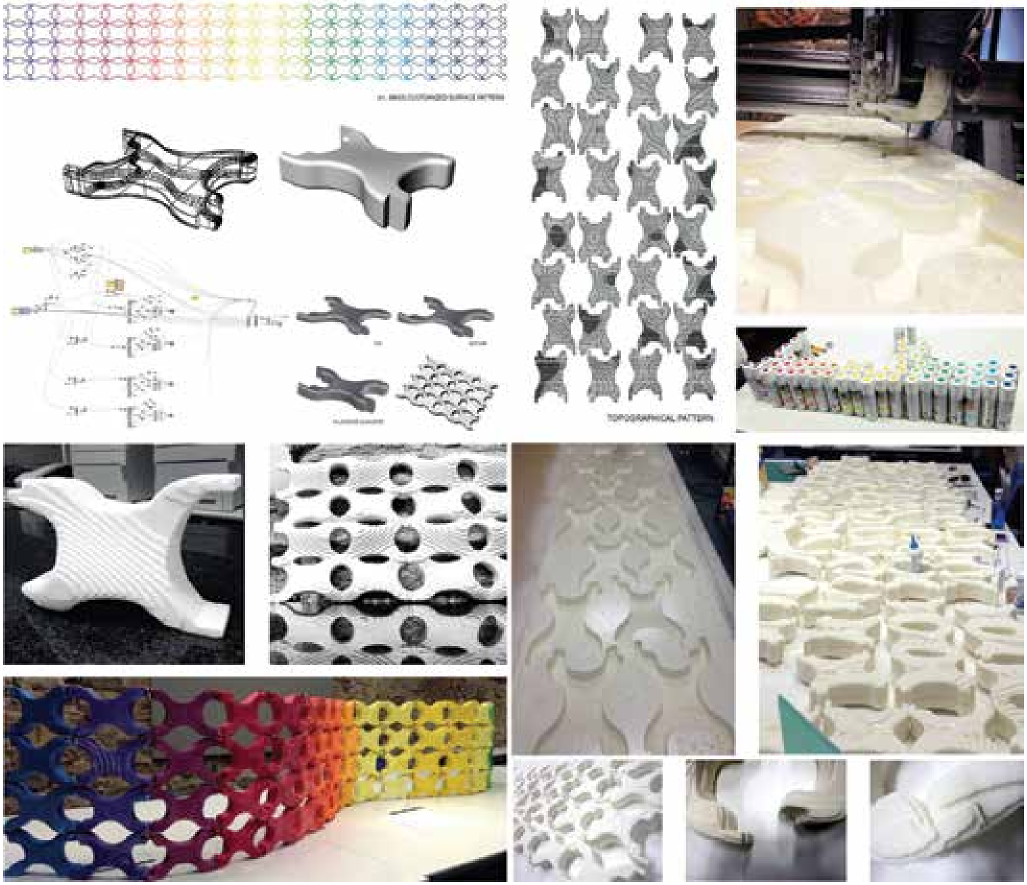

Figure 6
NuDL_Digital Technologies03_First Year.

PERFORMANCE_ (NON)OPTIMIZATION: NEW DISCIPLINARY CODES

Computer Code is the 21st century Architect's Tooling Apparatus, and as such it is irreducible to any of Architecture's traditional design taxonomies. Algorithmic thinking has entered design practices to irremeably transform them bottom-up. Code has become policy, albeit not in its restrictive sense but as generative protocol.

Performance needs to be theorized in order to move beyond modernist models based on a functionalist paradigm of efficiency and a mechanical approach to sustainability. Such a reductive notion of performance responds to a linear way of thinking that prioritizes the minimum use of material, structure and energy to fulfill single conditions. Paradoxically, it is also one that is in direct opposition to the non-linear dynamic nature of computational engines.

For the discipline of Architecture not to fully incorporate and reflect the enormous impact that Computer Science has had on all spheres of knowledge, is not a wasted opportunity but a retrograde act. If design research can attempt at becoming scientific method, there needs to be a complete consistency between technology-tool-technique-episteme.

Although only 5 years old, this academic program has attempted to propose richer and more complex approaches to the generation and evaluation of built forms to the extent possible and by means of diverse methods and exercises of diverse difficulty for an Undergraduate level (Figure 6).

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Dances with Architects

Interactive performance as a new concept for architectural design studios

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Abstract. *This paper proposes a complementary approach for the architectural design studio. By interpreting architecture by means of an interactive (dance) performance as design task it combines architectural theoretical examination with the implementation of new technologies and event realization. This design studio concept integrates scenography, choreography, sound design and event management, providing workshops carried out by external and internal experts to give insight into these disciplines and new tools. The experimental form allows the students to define the specific form within a broad scope, ranging from a dance performance performed by the students themselves to an interactive installation. The focus for the students was on dealing with the diverse input and on the decision-making process and its reflection.*
Keywords. *Interactive; performance; teaching; collaboration; gesture control.*

INTRODUCTION

The prevailing concept of design studios at architecture schools is that of simulating a design process in an architectural office. Consequently, a standard task may consist of designing a building or other objects in the context of the built environment. By contrast in an alternative approach several existing works combine architecture and dance (Bronet and Schumacher, 1999; Pekol, 2011) and served as a starting point for a new design studio concept.

In contrast to established concepts, this design studio has an interdisciplinary setting, using new media, dance and scenographic elements to translate architecture into an interactive performance. A central educational aim of the project described in this paper was to instruct the students to analyse and abstract architecture in order to be able to transfer the essential characteristics into a different medium.

The concept of this design studio involves a very broad range of topics so as to incite the students' learning process with a task that represents the complexity of the design process in architecture. The project therefore combines elements of architectural theory with an extensive number of efficient tools and basic introduction in choreographic and scenographic acting. As collective project the students involved have to clarify their specific art and technical skills and assemble all competences of the group for a presentable and conclusive stage event.

The future outcome being an interactive performance – instead of (relatively) theoretic drawings of an architectural object – fundamentally transforms the design and working process. Firstly, the students are introduced to completely new subjects, which are scenography, dance and man-machine interfaces (MMI). Secondly, they have to learn the use of hardware and software tools, and most importantly they need to develop the ability to decide which tools are best suited for their intention.

The project is based on an interdisciplinary cooperation between a department of the faculty of architecture and external specialists from the field of scenography, choreography, programming and visual arts. Accordingly, there are different levels and focuses in this project: the acquisition of expertise in handling the technical tools, the creation of a complex scenographical work, which included the work with dancers, and the organization of the event itself.

The course, which was named "Dances with Architects", was first offered in summer 2012 and open to advanced students. The students could choose to work on specific aspects of the project.

THE ARCHITECTURAL DESIGN STUDIO

Project-based learning has traditionally been an elementary component of the architectural curriculum with the design project as its centrepiece.

This innovative concept for the design studio aims at opening the narrow concept of learning environment (Webster, 2008) reflected in Schön's influential works 'The Reflective Practitioner' (1984) and 'Educating the Reflective Practioner' (1987). As Webster justifiably assesses, Schön limits everything to the formal one-on-one meeting between design tutor and student. Additionally his understanding of learning and teaching is based on the premise that teachers know the right solutions and that something like a generally shared aesthetic values exist.

Though Donald Schön's decisive works turned the focus from the accumulation of technical knowledge in architectural education to "reflective practice", which was defined as "the capacity to reflect on action so as to engage in a process of continuous learning" (Schön, 1983) the understanding of architectural education remains somehow limited (Webster, 2008).

On the basis of the aspects highlighted above and with the awareness that certain pedagogical settings, like tutoring and reviews, limit the students' possibility to express themselves elements were introduced to create a more informal learning setting. Therefore an essential part of this design studio project was for the students to decide which tools to use and how to convey their ideas, and to continuously reflect their decisions. And the output, i.e. the final 'product', was purposely not exactly defined in the preparatory phase.

Instead of defining how to present and represent their ideas the students were asked to define by themselves how and via which medium their proposal should be transported. And based on Schön's (1983; 1987) assumption that reflection plays an important role in the development of elaborate design expertise we introduced specific tools to facilitate this process, like the documentation book.

The establishment of groups, instead of the usually promoted individual works, pursued several objectives. Opening the narrowed learning environment concept, where the one-on-one tutoring is the central element, the group work takes into account the fact that students can learn as much from their peers as they learn from their teachers. And not only did the students work in small groups, but they had to organise the work of the entire studio and the event itself.

Whereas the basic structure of the design studio was defined beforehand – based on the premises and aims outlined above – some elements partly evolved in the course of the project due to its experimental character. This gave the opportunity to react to the needs and request of the students.

Documentation book

To reinforce and systematize the reflexive process each group was asked to draw up a book that should assemble all information, inspiration, sketches, images, etc. that appeared relevant to the students in forming their decisions. Beyond this rather intuitive collection of material this book should include explanatory texts that described the reasons for de-

Figure 1
Concept Collage: Created by student group working on the Barcelona Pavilion (1929) – upper row: Concept visualisations of interactive projection; lower row: images from the Barcelona Pavilion.

cisions taken in the different phases of the design process.

As explained above one reason was to collect as much design relevant information as possible. Another important aspect – which was communicated to the students – was to enable the students to rethink and if necessary to revoke decisions and go back in to that design phase.

CREATING AN INTERACTIVE DANCE PERFORMANCE

The objective of this project was the realization of an interactive dance performance using tools that would react to the dancer's movements. The project was based on cooperation with a scenographer and a choreographer. In the first phase, the students were presented with four different buildings from accredited architects. The students had to analyse the buildings and detect the main architectural themes. With these themes and metaphors in mind, they were asked to find the adequate form in translating them into a performance (Figure 1). In order to facilitate the students' progress in this new field, we included activities like visiting a final rehearsal at the theatre and a modern dance performance [1]. Furthermore, the students were asked to make improvisation exercises in order to develop a basic understanding of the language used in dance.

The next phase involved introductions to the different hardware and software tools and presentations with related topics. While becoming familiar with the different tools and aspects of this project, the students were given the choice to organise themselves in three different work groups: costume design, music and technology, and stage design. As the work progressed, the students organized all necessary coordination themselves and project management became an important and integral part of this complex work.

The main part started after the students had been introduced to this new area and gotten acquainted with the tools. The learning process still played an important role in the students' work process, and it shaped the ideas of what their work could look like. Not only were the students introduced to some examples of the enormous amount of interactive dance performances [2,3] that are being developed, but they also had to find their individual answer in relation to their abilities and the selected building.

The final performances – which will be explained in more detail below – cover a broad range reflecting the different architecture, which they try to translate. They range from the creation of interactive illusions (Mies) to an interactive installation based on design methodology (Haller) to a provoca-

Figure 2
Selected buildings: Barcelona Pavilion (1929), HTL (1966), Jewish Museum (1999), Rolex Learning Center (2010).

tive theatre play (Libeskind) and a colourful dance performance (SANAA). Some of the works focus on the choreography, others explore the effects, which can be produced on projections via Kinect sensor, and still others play a virtual game creating an augmented reality with the use of markers and specific glasses.

DESIGN STUDIO ORGANIZATION

As the setting and organisation of the design studio is quite complex, it will be explained in detail below. Whereby the emphasis is on the first two phases.

This architectural design studio project involved – to a greater or lesser extent – the following participants: architecture students (20), scenographers (2), dancers (2), choreographer (1), media artist (1), and architecture design tutors (2).

At the beginning the students were presented with a choice of buildings and were asked to work on the "translation" of these buildings in groups of five.

The selected buildings where (Figure 2):

- Mies van der Rohe, Barcelona Pavilion, 1929
- Fritz Haller, HTL, Brugg-Windisch, 1966
- Daniel Libeskind, Jewish Museum, Berlin, 1999
- SANAA, Rolex Learning Center, Lausanne, 2010

It should be pointed out that the students where given great freedom in creating their performance. They were free to decide if their concept would benefit from dance elements, if the dance elements would be performed by themselves or by dancers, or if the performance would not include any dance elements at all. It was continually made clear to the students that the choice of tools and elements was theirs and that their decisions should be based on their evaluation of the adequacy to support the interpretation of architecture with the language of dance and interactive media.

The following list presents all tasks that were part of the project (Figure 3):

- Creation of a performance based on famous buildings.
- Production of music or music compilation (using Ableton software).
- Event management (organization of dance performance event, including opening speech, catering, designing invitations, stage setting, etc.)

The first phase was a conventional architectural analysis, consisting of research about the history of the building, the architect(s), the most important historic trends and other relevant aspects of that time. As a kick-off, the professor for architectural theory made a presentation in which the buildings were introduced, focusing on the atmosphere.

In addition the students were asked to define the characteristics of the buildings and name three themes and metaphors for each. They were

Figure 3
Organisation of Architectural Design Studio.

informed that these themes and metaphors would help them translate the architectural work into another medium.

As outcome of the first phase the groups presented their findings. It became apparent that apart from a thorough architectural analysis, the groups tried to convey the atmosphere of the building by using pictorial metaphors and the like.

The concept of the design studio now foresaw to introduce the students to the language of dance. So the next phase started with a workshop carried out by the choreographer and dancer Patricia Wolf. The theoretical introduction briefly outlined the *"Labanotation"*, a system that analyses and records the human movement developed by Rudolf von Laban (1991).

Based on Laban's basic explanation of how space is viewed and experienced in dance, the *"Improvisation Technologies"* developed by William Forsythe (1999/2003) were introduced. With the improvisation exercises presented in the related video (and some other improvisation techniques) the students had to create short choreographies within one hour. They either worked with changing rhythms or they used words to create and perform an improvised choreography.

Simultaneously a new task was assigned to the students, which required analysing the building based on movements. The student groups consequently studied the ground plans of the buildings and tried to trace the movements of an imaginary visitor. The students depicted the movements by drawing curved lines for lines of movement and marked spots where the visitors' attention was attracted so that they came to a halt. This analysis was intended to serve as a base for the design of their future choreography. As we will see later this proved to be true only for some of the student groups.

The students presented the outcome of this analysis at the end of the 2nd phase. The presentation was composed of two parts: the first part was a slide presentation featuring the "movement analysis"; the second part was a live performance or video presentation of a small choreography, which they had created transferring the movements through the respective building into dance elements.

Concurrently the second phase introduced the students to the new software and tools. This was done through presentation, demonstrations and intense workshop sessions. For this project the main focus was on the interaction between graphics developed with Processing, the Kinect sensor and human movements.

The third phase, *Concept + Cooperation*, follows the normal structure of a design studio, with intense work by students and regular discussions and coaching with the design tutors. And the fourth and final phase consisted of the production of the various elements of the performance and organisation of the event.

APPLICATION OF SOFTWARE AND HARDWARE TOOL

In the course of the project the students had to develop their expertise in the use of different software and hardware tools. In this case: Ableton Live, an audio/music production software, which they used not only to arrange tones, but also to modify music they had produced by analogue means; the video mapping software MadMapper that enables users to define the form of the projection. The open source programming language Processing was selected to use the gestures captured by the Microsoft Kinect sensor to transform projections.

The technical implementation of the performances is based on the integration of gesture capture by the Microsoft Kinect device and their connection with different tools of acoustic and visual output. In detail, the students were basically introduced in the use of the Ableton Live sequencer as a tool for music production, the video mapping software MadMapper and the integrated development environment Processing for interactive graphic presentation. All these tools offer a direct connection to the Kinect sensor and allow immersive conversion of the dancers' movements by tracking specific parts of the human body.

Created Performances	Dance elements	(Interactive)projection
"MIES in motion"	Yes	Yes
"HALLER interaktiv"	No	Yes
"Decertatio" [Libeskind]	Yes	No
"Colour feelings" [SANAA]	Yes	(Yes)

Table 1
Categorization of (dance) performances.

CREATION OF PARAMETRIC DANCE COSTUMES

The concept of this interdisciplinary project foresaw a development of the dance costumes using parametric design methods. Therefore, a three-day workshop for Rhino and Grashopper was held to provide a profound introduction to the parametric design. In addition to that, a broad range of devices was made available to the students in the department's laboratory. This included a 3D printer and a laser cutter; the latter had been chosen by the students because of its easy handling and suitability for the task.

As the starting point for developing the costume, the students selected a central element of the choreography, which consisted in the idea that the dancers would open the imaginary boundary, the so-called "fourth wall", between themselves and the audience. The opening up was expressed through the dissolution of the costume, which consisted of two layers. The first layer, a simple fabric band wrapped around the dancer, was slowly unwound. The second layer mainly constituted the costume and was produced with the laser cutter. The pattern was created with the use of Rhino and Grashopper on the basis of a parametric design patterns.

INTERACTIVE (DANCE) PERFORMANCES

Due to the experimental form the four student works vary considerably with regard to conception and execution. To expand on this variety with more detail, Table 1 presents a categorization and the following summaries shortly describe the content and differences of the student works.

The *"MIES in motion"* sets its focus on the aspects of materiality and space and perception. Images of the surfaces where projected onto a special screen. The dancer's movement in front of the screen modified the projected graphics. The accompanying music or sounds had been created analogue by recording sounds that interpreted the used materials.

The work *"Haller interactive"* was not referring only to the selected building (HTL), but in response to Fritz Haller's universal design method focused on the topics regularity, modularity and order. The students decided that the best representation would be to create an interactive installation resembling a computer game. By playing this interactive game, which was composed of augmented reality and interactive elements, the participants intuitively learned the rules (Figures 4 and 5).

In conformity with the prevalent atmospheric power the work *"Decertatio"* interprets Libeskind's Jewish Museum as a theatrical enactment. In the centre of the production stand disorientation, provocation and conflict. Set in a black box the audience was placed in a square in the centre of which a seemingly lost dancer danced in a spot light, while an actor recited a text that expresses conflicting emotions.

The performance *"Colour Feelings"* enacts SANAA's Rolex Learning Center as dance performance with the students themselves as dancers. Each spatial impression is represented by an own scene characterized by a specific colour and performed by one of the students. Interactive projections that react to the movements reinforce the impression but play a minor role. In each scene one person personifies the visitor, and another person the built environment. The performance ends in a scene where all dancers come together and leave their 'marks' expressed by the specific colours on the surrounding.

CONCLUSION

Related to the complex task of developing an interactive dance performance, the structure of the design studio was equally complex. As a first evalu-

Figure 4
Augmented reality set-up ("Haller interactive").

ation, we can point out that the unexpected combination of theoretical aspects of architecture with the management and organization of a public performance and the integration of modern soft- and hardware applications leads to challenging but also very stimulating tasks for students. Setting up this project therefore activates competences in various ways. On the one hand, it brings students into close, direct and playful contact with software and techniques like rapid prototyping, gesture recognition, sound editing or visual programming. On the other hand, it establishes a strong and intense link to architecture itself and forces students to reduce the intentions of architects and their buildings to very essential statements. Combined with a high motivation of the participants, the management of a public performance requires cooperation on different levels and functions. In this context, the project supports students' skills in cooperation, time management, budget and the interaction with a group of specialized participants.

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Figure 5
Video glasses and sound system for augmented reality set-up ("Haller interactive")

A Case Study in Teaching Construction of Building Design Spaces

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Abstract. *Until recently, design teams were constrained by tools and schedule to only be able to generate a few alternatives, and analyze these from just a few perspectives. The rapid emergence of performance-based design, analysis, and optimization tools gives design teams the ability to construct and analyze far larger design spaces more quickly. This creates new opportunities and challenges in the ways we teach and design. Students and professionals now need to learn to formulate and execute design spaces in efficient and effective ways. This paper describes curriculum that was taught in a course "8803 Multidisciplinary Analysis and Optimization" taught by the authors at Schools of Architecture and Building Construction at Georgia Tech in spring 2013. We approach design as a multidisciplinary design space formulation and search process that seeks maximum value. To explore design spaces, student designers need to execute several iterative processes of problem formulation, generate alternative, analyze them, visualize trade space, and address decision-making. The paper first describes students design space exploration experiences, and concludes with our observations of the current challenges and opportunities.*
Keywords. *Design space exploration; teaching; multidisciplinary; optimization; analysis.*

INTRODUCTION

In the current practice, the process of designing buildings is rapidly becoming more collaborative and integrated through the use of Computer-Aided Design and Engineering (CAD/CAE) technologies. However the use of these technologies in the early stage of design is limited due to the time required to formulate and complete design cycles. A new class of technology, involving automated multidisciplinary analysis and design space exploration is increasing by the order of magnitude of the number of alternatives that a design team can generate and analyze (Haymaker, 2011). This creates new challenges in the ways we educate tomorrow's designers and managers in schools of architectural, engineering, and construction. Students and industry professionals must learn to work together to formulate and construct design spaces in order and understand performance trends and trade-offs to solve issues central to practice.

Geordia Tech's curriculum demonstrates an important issue in digital design education. Georgia Tech's Schools of Architecture, Civil Engineering, and Construction, offer a variety of courses in design studio, design theory and process, computer-aided design (CAD), building information modeling, parametric design, energy analysis, structural analysis, cost analysis, decision analysis. However our Institute lacks integrated courses that help students un-

Figure 1
Design professionals gave design challenges that students formalized into multidisciplinary building design space exploration processes.

derstand how to work together to systematically formulate, execute, and understand multidisciplinary building design spaces.

Several organizations and associations such as the American Institute of Architecture (AIA) Technology in Architectural Practice [1], the National Council of Architectural Registration Boards (NCARB) award for the integration of practice and education [2], the American Society of Civil Engineers (ASCE) excellence in civil engineering education teaching workshop series [3] and the Associated General Contractors of America (AGC) BIM Education program [4] support the efforts of academic programs to create and implement effective new curriculum that bring together students from multiple disciplines, industry professionals, and advanced design technologies to learn to address practical design challenges. To address this need, some curriculums are emerging in architectural schools such as Columbia University, Harvard University (Kara and Georgoulias, 2013) and University of Southern California and Stanford University (Gerber and Flager, 2011).

This paper describes new curriculum under development in Georgia Tech's Schools of Architecture and Building Construction that engages architecture, engineering, construction, and computer science students and industry professionals in collaborative multidisciplinary design space construction and exploration processes. The curriculum engages students in a team-based approach to problem formulation alternative generation, alternative analysis, design space exploration and optimization, and trade-space visualization and decision-making.

METHODOLOGY

The methodology in this course consists of five phases that are described in more detail below: Problem formulation, alternative generation, alternative analysis, design space exploration and optimization, and trade space visualization and decision making. The students utilize these phases to construct design spaces for the professional challenges in the semester long group project.

Problem formulation

In this first phase, we engaged professional designers to present challenges from their own practice that they felt could have benefitted from more exploration if they were given more time and better tools. Figure 1 and the following text describe the challenges presented by the design teams. The benefits of engaging design teams in this way were twofold. It helped students confront real world design challenges without needing to spend too much time gathering information about them. It also gave professional designers access to new design space

Figure 2
A preliminary Wecision model developed by a group of students to define the project goals and objectives, including the units and criteria for measurement.

exploration tools and ways of thinking about their challenges.

- Case 1: Cancer treatment center
  A new cancer treatment process provides an opportunity to develop a new design methodology. The professional design team found the massing phase challenging because of the very large equipment involved with the new treatment process. Several programming and crane access issues constrained the potential solutions somewhat, but the design team was interested in more systematically exploring the tradeoffs of different building massing in terms of their visibility from highway, energy consumption, daylight factor, sensitivity to adjacent neighbors, and connection to adjacent green space.
- Case 2: Children's hospital
  The hospital, located in the Middle East, was conceived to emphasize western healthcare ideas such as patient comfort, equality, and external views. The students were asked to evaluate the current proposal and provide insight into how the geometry and solar shading could be modified to improve solar and day lighting performance, thermal gain, and patient views. The design team focused on the trade-off between designing for solar radiation and day lighting factor; however, other factors contributed to the final evaluation including total square footage and aesthetic attributes.
- Case 3: Mixed-use tower
  The tower in china was conceived with the vision of a "the Breathing Tower" that uses green energy techniques, including passive lighting and ventilation. The student's goal in analyzing the design for the tower involves optimizing the quality and comfort levels of the occupants. They look at performance criteria such as daylighting, passive ventilation, structural stability and attempt to preserve the grace and symmetries of the original design aesthetic, while keeping costs at a minimum.

Students first used Wecision's Choosing by Advantages model (Abrams et al., 2013) to model the organizations involved, the goals and constraints they needed to consider, the range of alternatives they wanted to explore, and the preferences on outcomes (Figure 2). They also enter initial estimates of what they believe the outcomes are likely to be based on intuition.

Students then developed Meta Model (MM) in System Modeling Language (SysML) to describe the structural and behavioral aspects (Reichwein and Paredis, 2011) of their design challenges. The MM is an abstract model of the data of the actual geometric model. It captures the structural aspects of the model such as domain specific semantics, attributes and relationships among parts through block or class definitions. From these definitions multiple

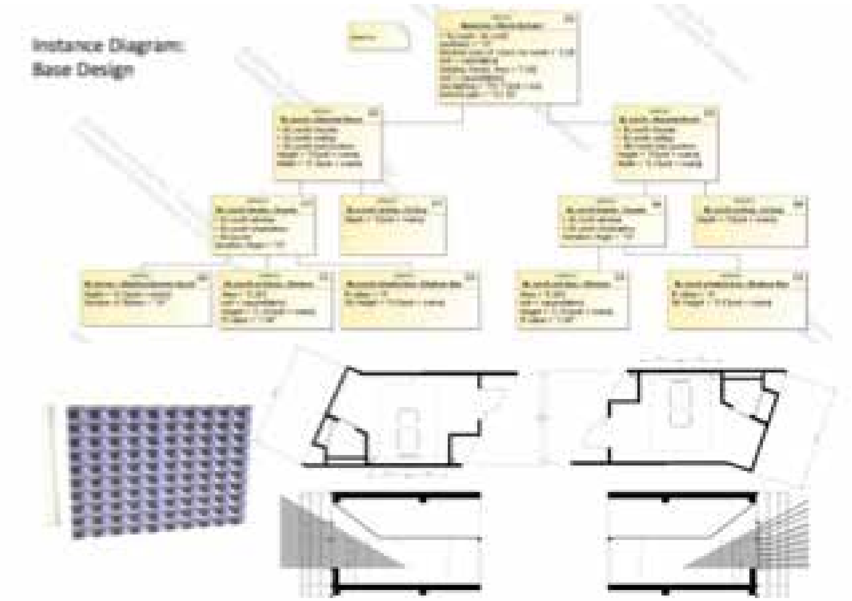

Figure 3
A SysML block instance diagram describes the data blocks and relationship used to generate alternatives for the room dimensions in a children's hospital.

Instance Models (IM) of design alternatives can be generated by changing the parameters. The behavioral aspects of the challenges are captured though activity diagrams that represent the sequence of actions to be performed in order to generate, analyze and select a design alternative that describe the generative and analytical systems in their design spaces.

They used SysML Block and Instance diagrams (Figure 3) to describe the alternative's components and relationships that will be important in the analysis, and SysML Activity diagrams (Figure 4) to describe the analysis processes they wish to perform on these models. In these diagrams they explore and communicate the detailed input parameters for analysis tools, as well as the output parameters of the analysis, and whether they are to be minimized or maximized.

Alternative generation

In the second phase, to represent the design alternatives geometrically, students then made associative parametric design models that are driven by the design variables specified in the MM. In some cases custom scripting is also included to enable topological transformations that are difficult to achieve using parametric logic alone. The students tested the parametric model and generated different alternatives by modifying the variable values (Figure 5).

Students used commercial parametric design tools such as Rhino/Grasshopper, Revit, and Digital Project to generate the parametric model. Output of these tools would be a set of architectural forms in which their geometry and properties are easily modified by changing the parameters.

Alternative analysis

In this third phase, the integration of their parametric model with analysis tools allows students to analyze and evaluate the performances of different alternatives in a design space and compare them based on their performance metrics. To this end, students need to integrate CAD and CAE tools in a way that the data flows between the tools in an au-

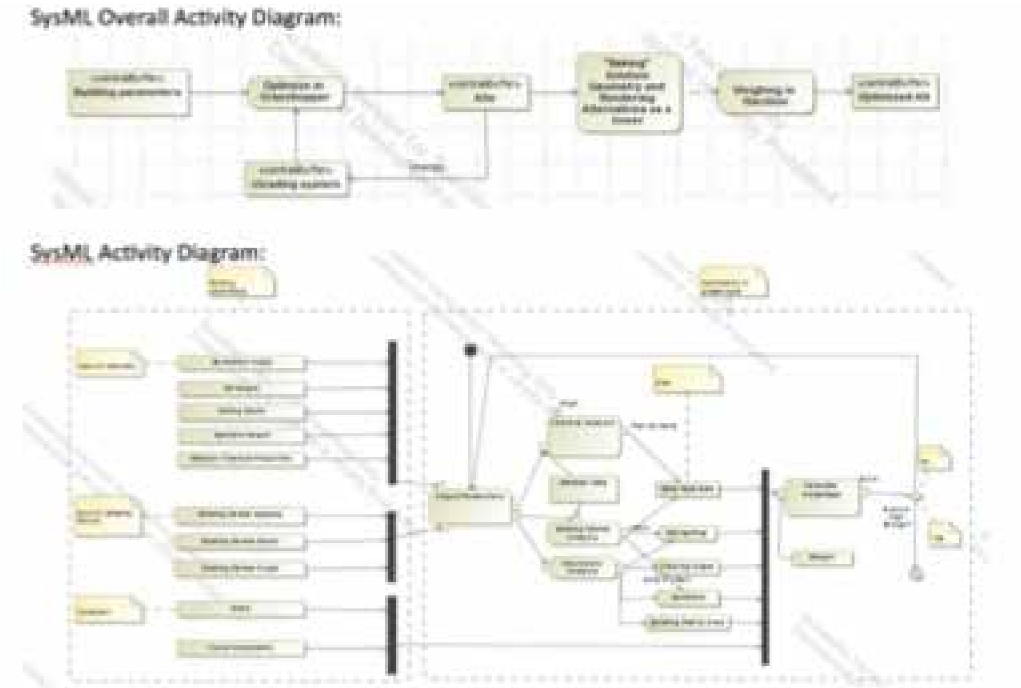

Figure 4
A SysML activity diagram describes the high-level integration and optimization process, as well as detailed processes for each goal analysis.

tomated fashion to reduce design cycle latency. The simulation and analysis tools were selected based on the performance objectives, inputs, and familiarity from among available commercial software such as EnergyPlus, Green Building Studio, eQuest, DIVA, and IES VE for energy analysis, SAP2000, GSA Oasys, STAAD, Karamba, and ETABS for structural analysis, Radiance, Ecotect, DIVA, and Daysim for Daylighting simulation. Figure 6 shows student daylight analyses comparing the original design team's design with one of the alternative's generated from their parametric model.

Students were introduced to experimental workflows such as ThermalOpt (Welle et al., 2011) and BiOpt (Flager et al., 2013) that build in data transformations and strategies that help prepare models for fully automated simulations and contain domain specific knowledge necessary for more efficient optimization. Students were also encouraged to develop their own workflows, for example students in the high-rise group developed a customized workflow to minimize the total structural weight. The developed workflow is able to calculate the wind pressure on the façade based on ASCE 7-10, calculate tip deflection on the top of the building, and modify the columns' cross section until achieving the most efficient column sections (Figure 7). Students in the Cancer Treatment Facility developed several geometric scripts to analyze designs automatically for visibility from the highway, sensitivities to adjacent buildings, and access to open space (Figure 8).

Design space exploration and optimization

Due to the potential size and complexity of potential building design spaces, analyzing and testing for every parametric variation can be impossible. Additionally, many of the design objectives are hard to formalize, and so it is often more fruitful to en-

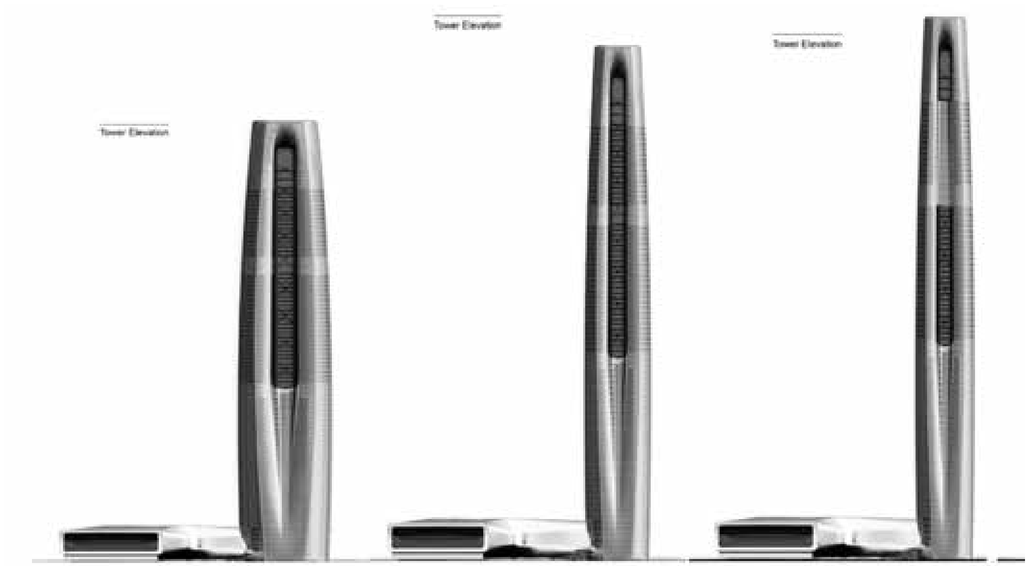

Figure 5
A range of tower designs generated from the student's parametric model.

able the designer and tool to work iteratively visualizing and generating aspects of the design space. Hence, in this fourth phase, the students learn to apply computational techniques such as design of experiments and use optimization and sensitivity algorithms to systematically guide the generation of alternatives. Students used commercial design exploration and optimization tools such as Octopus and Galapagos by Grasshopper, and ModelCenter.

Trade space visualization and decision making

The visualization of performance enables students to engage in computer-based exploration and visualize tradeoffs. In this final phase, the students learn how to use Pareto frontiers, performance trends, and sensitivity analyses in order to make informed decisions in guiding the optimization process. They used the built in tools provided by ModelCenter and Wecision. Figure 10 shows two examples of student approaches to exploring the multidisciplinary design spaces.

At the end of the class, students return to Wecision to identify several prominent alternatives in the design spaces they explored, and to report on the multidisciplinary performance and weigh the importance of the advantages of each alternative. At the end each alternative is evaluated based on its total advantages.

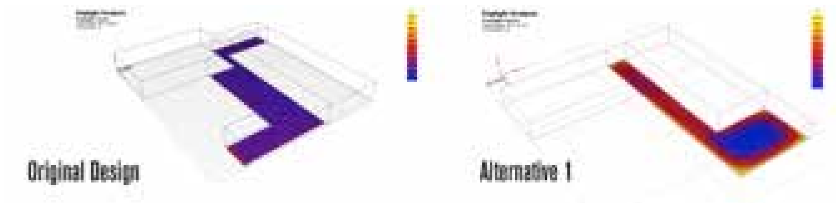

Figure 6
Students analyse alternative designs for structural performance, daylight, energy, cost and more.

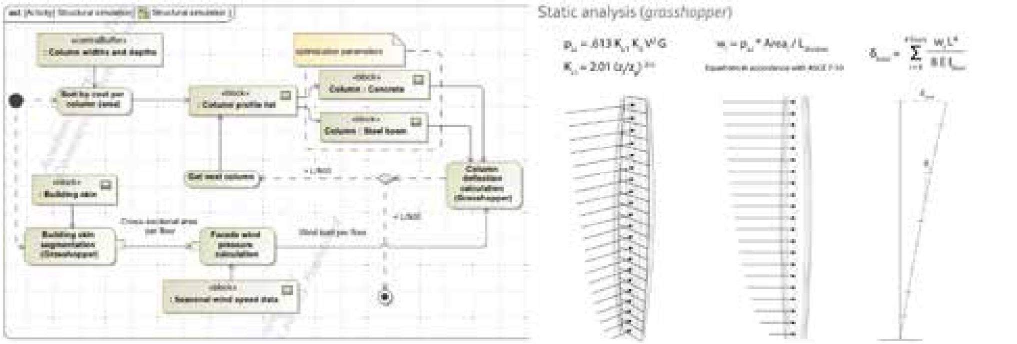

Figure 7
Students developed a custom process for analysing high-rise structural performance.

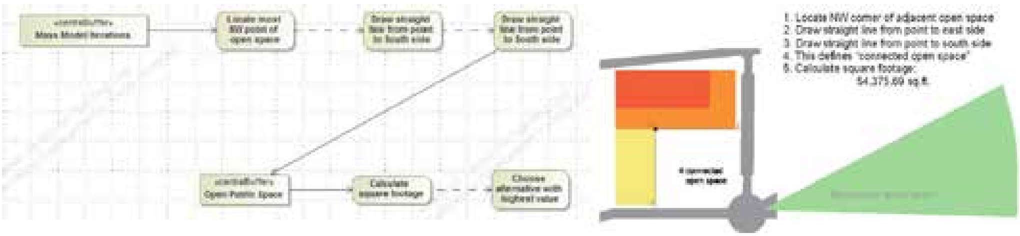

Figure 8
Students developed a custom process for analysing the projects relationship to adjacent green spaces.

CONCLUSION

This paper described an exploratory class in which students from multiple disciplines worked with industry mentors, and learned how to formulate design space exploration problems, parametrically define alternatives, integrate CAD and CAE tools to rapidly analyze alternatives, explore design spaces and trade-offs, and make and communicate decisions. Students learned to build and integrate models to iteratively search through a space of designs and negotiate to find the best and most sustainable designs. We discuss several challenges in teaching the class, and discuss ongoing work to overcome them.

Improve team formation

Students appreciated the multidisciplinary teams in which students have individual domain knowledge

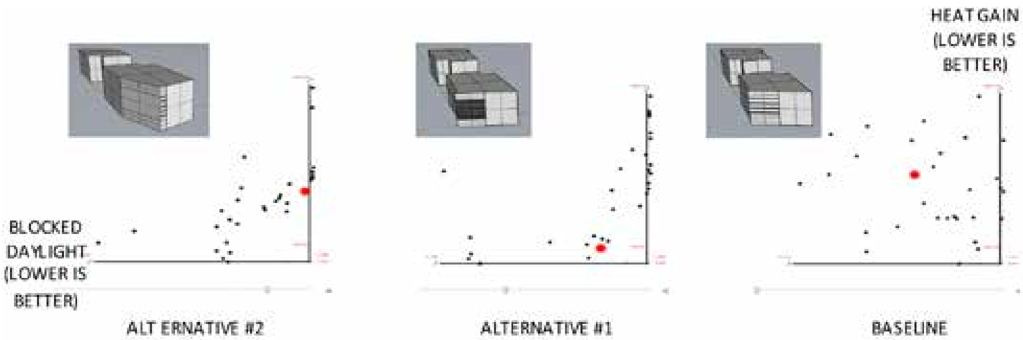

Figure 9
Students developed an optimization process, each team found designs that outperformed the industry chosen design, for the objectives analysed.

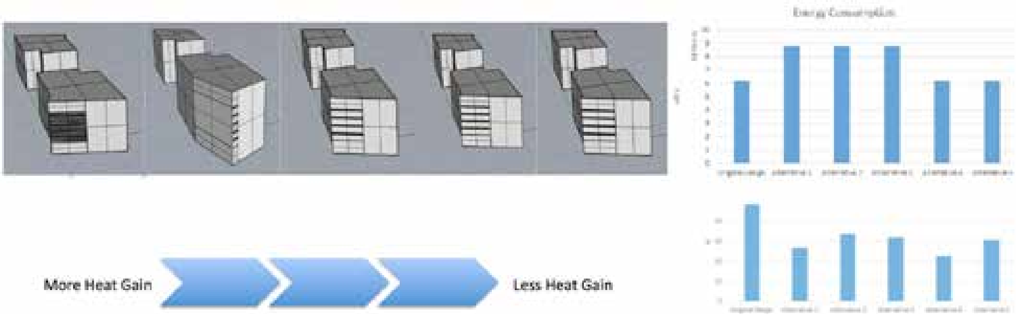

Figure 10
Students experienced with different methods of exploring and communicating design space exploration information.

and skills to contribute. Each teams requires an appropriate mixture and level of domain knowledge in the programs as well as general computer scripting. In future versions of the class we plan simple tutorial exercises early in the class, and delay choosing teams a few weeks until we have developed a better understanding of student skills and interest.

Separate learning of concepts from applying concepts

We taught students the concepts and tools directly in the context of the industry problems. This was

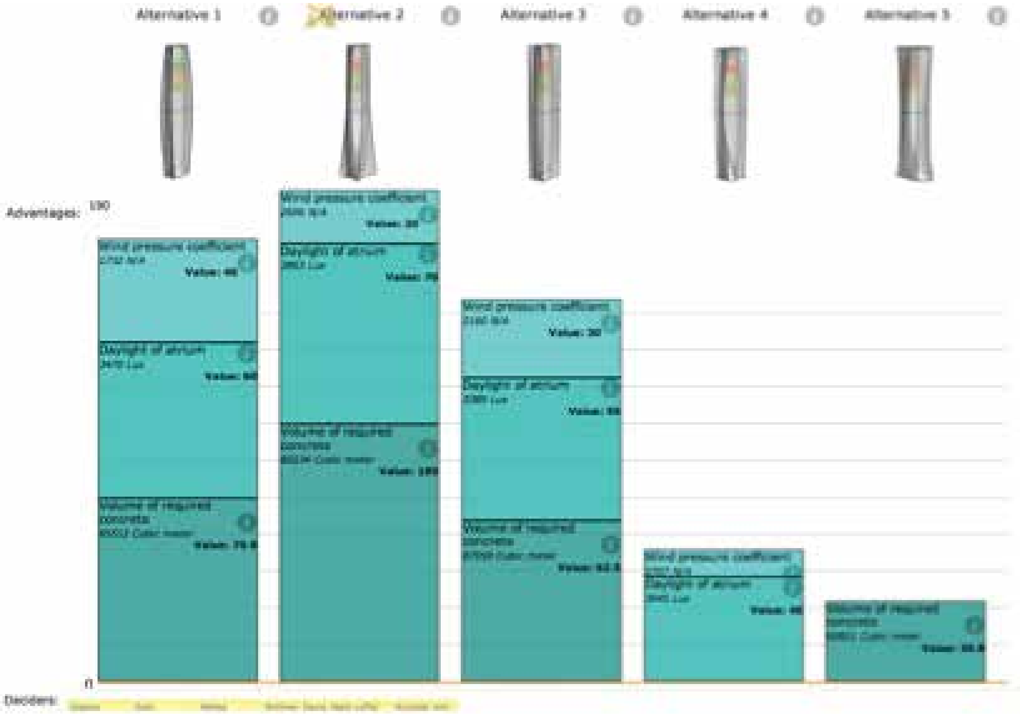

Figure 11
A final Wecision model that communicates the multidisciplinary advantages of a selection of alternatives in the design space.

difficult because of the large number of concepts students needed to absorb at one time, and the fact that there was no ground truth to determine if students were applying the concepts "correctly." We are creating a series of short tutorials for a simple example that teach students the fundamental concepts of design space exploration. Students will begin to learn about the industry problems early in the class, but will not begin to apply these concepts until they have completed the introductory tutorials.

Improve integration of tools

While several workflows are emerging, some workflows are very complex, and require better documentation for students to be able to apply them. Others are overly simple, and students quickly run into objectives they cannot analyze, alternatives they cannot generate, and spaces they cannot explore because of limitations of one workflow or another. Another important area to improve integration is between meta modeling tools like Wecision and MagicDraw with CAD and analysis tools. Despite the limitations in terms of integration, the meta, parametric, analysis and decision models co-evolve during the design exploration process. Not all the knowledge integration occurs at the tool level. For example, while the students implement the parametric model based on the meta model they also evolve the meta model by adding, deleting or editing attributes required by the actual parametric geometric model. Therefore, the issue of integration it is not only related to implementation of the interoperability among tools, it is also related to the development of co-evolution (Dorst and Cross, 2001) mechanisms and methods, since the different models are abstractions that represent only aspects of the design challenge interacting with other aspects.

Improve ability to systematically frame, define and formulate the challenge

This process is beneficial to the designer when there is a schematic idea, with strong initial intuitions for effective performance. For time efficiency a well thought out schematic will cut down on the parametric ranges, allowing quicker model building and computational processing time. There are very few prior cases to look to understand best practices for how designers best frame design exploration problems, how to choose the right objectives, and parameterization of the problem. Through better metrics for describing challenges, and more case studies that illustrate good and bad problem formulations, we would be able to improve the efficiency and effectiveness with which students formulate design problems.

Improve the ability adopt and adapt the right strategy to the right challenge.

Given a clearly understood set of objectives, students have difficulty identifying and applying the right strategy. We teach students to explore the sensitivity of each input parameter and the influence of weighting the different goals in each challenge guides to the next set of decisions. However, we need better documentation of the strategies that are available, and better assistance in finding the right strategy for the right challenge.

Improve the ability to assess and compare explorations.

Ultimately as designers we want to choose the strategies that enable the best exploration, and as instructors we want to be able to evaluate and guide students towards ever better exploration, Research is ongoing to define the metrics for assessing the efficiency and effectiveness of design exploration (Clevenger et al., 2011; Senescu and Haymaker, 2013). Development and integration of these metrics into design systems will enable students assess and compare their own explorations to those of other students and professionals on similar challenges.

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Innovative Learning for Collaborative Design in Ergonomics

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Abstract. *The proposed article deals with introducing collaborative architectural design into the training of ergonomists at the Master 2 level. The collaborative design workshop aims to confront ergonomists with the difficulties any design project involves, and which challenge architects, designers, engineers and so on: collaboration between people with different skills and different expertise; powerful time constraints; need for their work to converge; working together and/or at a distance; sharing documents; decision-making, etc. The article will present a short review of work carried out in the domains of architecture and design, and of the contribution of ergonomics within architectural projects. We shall then present the workshop's educational aims, and give details of the way it functioned. Finally, observation results will be presented and discussed.*
Keywords. *Collaborative design; architecture; ergonomics; training workshop.*

COLLABORATIVE DESIGN LEARNING IN AN ARCHITECTURAL PROJECT

Architecture and design

An architectural project generally depends on a context – temporal, geographical, political and economic. From the earliest design phases it includes different skills areas such as engineering, ecology, law, ergonomics and sociology (Hubers, 2009). It has to respond to a program taking account of a certain number of parameters – technical, social, environmental, industrial, legislative, political, etc. It develops in an increasingly restrictive regulatory framework, and since the 90s a variety of research has shown that it is rarely led by a single individual (Visser, 2002). Faced with competition, short deadlines and complicated quality and regulatory requirements, architecture firms have to innovate, using interdisciplinary design methods that combine the different skills and tools needed to bring the project to completion (Farel, 1995; Bucciarelli, 2002).

Nowadays architects no longer work alone, but collaborate with engineers, landscapers, designers, economists and so on. So the project becomes collective, uniting a variety of skills and knowledge that are all involved from the earliest design phase.

These particularities lead to consider design in terms of skills and collectivity (Cross et al., 1995; Jeantet et al., 1998; Larsson, 2005; Bucciarelli 1988, 2002; Minneman, 1991). This means that the activity of design combines collective actions, as well as the individual actions of different experts (Pahl et al., 1999). It is not simply a matter of assembling points of view. It is the result of interaction between the different components of the project, subjective in character (Pousin et al., 1986) and the consensus achieved between all the players who participate in designing the architectural project.

Such collective activity also obliges participants to use instruments of sharing, without which it would be impossible (Boujut, 2000). The aim of most of these instruments is to facilitate cooperation between those involved in a project, by making it easier for them to exchange information at different times and at a distance. They are only used, however, when the project is sufficiently advanced.

The sketch-phase, when important design choices are made, continues to make little use of such instruments of collaboration. Yet it is essential for the start of design activity in an architectural project that participants be able to meet despite distance, and communicate in real time. Sharing-instruments aim to facilitate exchange. Exchange is important in constructing what cognitive ergonomists call "cognitive synchronization", "temporal-operational synchronization", "mutual awareness" or "common operative references". All these concepts have already been defined in the field of cognitive ergonomics and constitute "the backbone of the collective resolution of a design problem" (Darses, 2004).

Ergonomics and architecture

Various works in ergonomics has explored different positions for the ergonomist within architectural projects, wishing to reinforce the dialogue between project management and ownership (Martin, 2000). Diverse experiences of participating in design projects have made it possible to identify the positive contributions of each position as well as the main stumbling-blocks: weak ownership which delegates the whole project to its management; projects mainly oriented towards technical or financial possibilities; a residual place accorded to future and possible human activity.

The real question about the ergonomist's contribution in the design process is that of his/her position. Is s/he a specialist, expert in the human factor, called on at precise moments? In this first case, s/he remains outside the design process and the main players use what s/he gives them whenever they think it opportune. Is s/he a potential actor in the design process, able to provide clarification about future and possible activity and to give structure to the design collective? In this case s/he is included in the design process, *within* the collective of those involved, and takes full part in debate, orientations and the choices finally made (Beguin, 2004; Daniellou, 2004). The latter is our point of view (Folcher, 2003) and the *raison d'être* of the workshop offered in the Master 2 professional training, whose main issues we will spell out below.

EDUCATIONAL AIMS AND HYPOTHESES

The training workshop in collaborative design's first aim is to create a cross-disciplinary, collaborative design milieu with its own tools. The design approach adopted is that of design-for-use (Folcher, 2010), which relies on methodological tools from the field of ergonomics to achieve overall understanding of projects and a broader exploration of design possibilities.

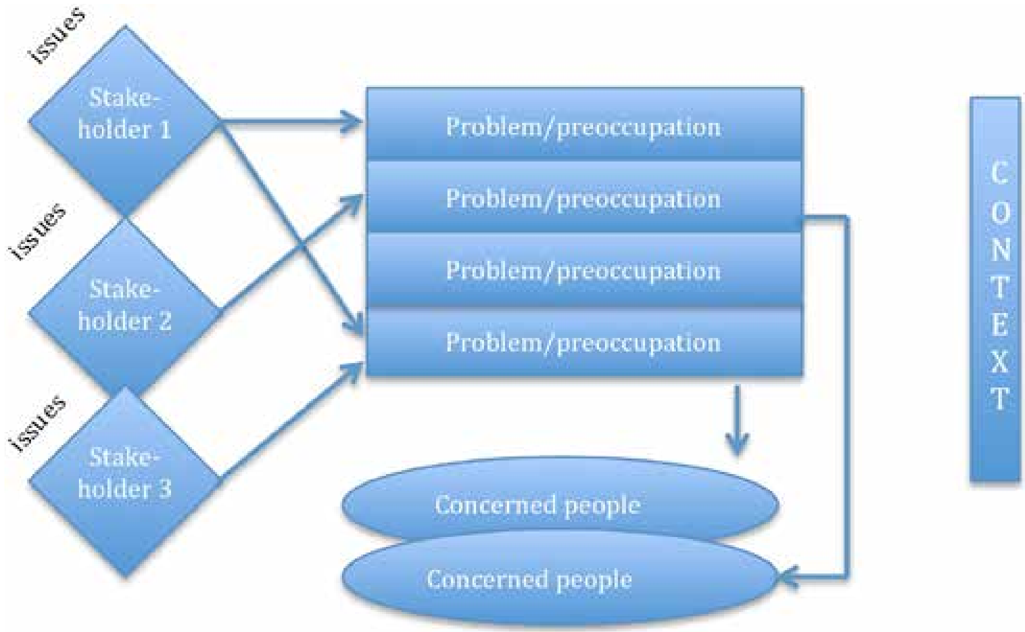
The second aim is to accompany students of ergonomics and design in the gradual construction of shared references for the possible forms of future activity. In another words, it means allowing and equipping the construction of common operative references (de Terssac and Chabaud, 1990).

The third aim is to accompany and structure rapid exchange between ownership and management of the project throughout its duration, all the way from the earliest schematic models to projections in physical space.

The design exercise proposed in the workshop, through a lived experience of collaborative design, is conceived with a didactic goal and has certain characteristics which ensure its ecology: a variety of actors express their potentially-contradictory points of view on the project; collaborative design activity unfolds in two different situations (physically present, and at a distance); the exercise is time-limited; a final result in the form of a sketch is required.

Two hypotheses underlie the workshop:

Figure 1
Social analysis of the project.



1. The first is that collaboration in design requires tools to enable designers to develop a broader vision (of the diversity of stakeholders and the plurality of issues involved) and construct shared references to the future, possible human activities when taking account of all the constraints that arise.
2. The second, more exploratory hypothesis seeks to document the way the design collective exists in two distinct situations: when physically present and when working at a distance.

PROPOSED METHODOLOGICAL TOOLS

The design-for-use approach to collaborative design articulates two methodological tools.

The first is a tool for social analysis of the project, used by practitioners of ergonomics to structure their interventions. It details the preoccupations and/or problems expressed by each stakeholder, and their issues; it presents the people likely to be concerned by the preoccupations and/or problems expressed; and it makes explicit relevant elements of the context. Figure 1 provides a schematic illustration.

The second tool is an enlarged method for exploring the possibilities in design, which are structured according to three broad types of contribution:

1. The project management contribution: exploring questions about the will to change and create new things. They address the way the project is piloted and how it develops, considering all the elements deemed relevant: political, strategic, financial, temporal, human;
2. The ownership contribution: exploring questions about how the will behind the project is made concrete in the form of something viable. They guarantee the feasibility of achieving the project on various levels: technical, legal, security, ecological, human;
3. The end users point of view contribution: exploring questions from the point of view of future, possible activity at the heart of the

project. They address the way general human characteristics are taken into account, as well as the specific, multi-determined human activities in the precise situation.

This method takes the form of a table which students complete as their developing projects unfold. An extract from the method used in the projects will be presented in the results section.

COLLABORATIVE DESIGN WORKSHOP: PRESENTATION

Two groups of 5 students (ergonomists and designers) took part in the collaborative design workshop, accompanied by three student observers (ergonomists) for each group, so as to record the process and analyze it at the end of the experience.

Thus in this workshop students in ergonomics were either designers or observers, whereas design students exclusively played the role of designer. Each group within the collaborative workshop was asked to design a secondary school for 240 pupils. They had to comply with a set of constraints in the program they were given, and were invited to implement an innovative approach to design enabling them to imagine and design a school which would be "different" from the way schools are traditionally conceived (Figure 2).

Four stakeholders who originated the demand for the school design set out their points of view on the project, and the issues involved: the Mayor of the town where the school would be located; a member of the regional council with responsibility for questions of disability and accessibility; a representative of the building standards department; and the future head teacher of the school. Throughout the design procedure students were also helped and guided by two engineering-architecture trainers, who advised and helped them with the presentation of their ideas and thoughts.

1. The design procedure fell into four phases:
2. Forming and presenting the exercise, the working context, listening to the four stakeholders, and learning to use the SketSha software in the distance-working situation;

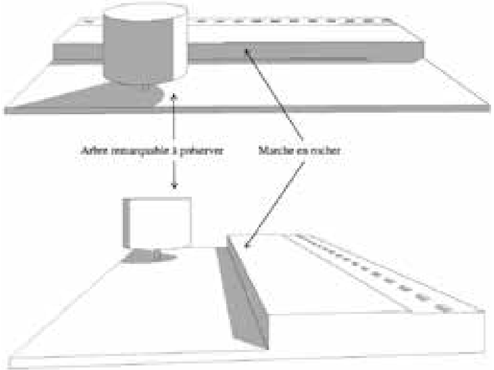


Figure 2
School design outline (extract).

3. Collaborative design working physically together;
4. Collaborative design working at a distance using SketSha software;
5. Finalizing ideas and presenting the project.

In the distance-working situation, designers were able to work simultaneously with the help of an innovative technological tool, the *Studio Digital Collaboratif* developed by LUCID of Liège University. It enables virtual working meetings to take place, at which participants can share spoken exchanges as well as any sort of document they have brought – these documents can also be modified and annotated graphically in real time (Ben Rajeb and Leclercq, 2012).

RESULTS: PROJECTS PRODUCED AND DESIGN PROCESS

In the time allowed, the two groups produced projects that explained the main lines of orientation and justified the choices they had made, and delivered a final graphic sketch:

- Group 1 opted to design an "innovative school that makes culture more visible and the town more attractive". They called their project ART'CADEMIE (Alexandre et al., 2012).
- Group 2 focused on "a school for everyone, a place where activities can meet". They called their project ECHOLOGIA (Houidek at al., 2012).

Analysis of the way the design process unfolded shows the existence of 'moments' which gave structure and rhythm to the collaborative design activity in the groups (see Table 1):

- Moment 1 *"Brainstorming"*: consisting in social analysis of the project on the basis of what the stakeholders said, and construction of an overall vision; initial structuring of the project's general orientation. Students were physically present, producing documents to illustrate and synthesize their ideas. During this period an overall vision of the project is constructed gradually: the stakeholders, the problems and preoccupations they express, and the people likely to be concerned by those problems, are at the heart of the project. This vision is the basis for preliminary sketches on paper, resulting from oral exchanges between the different designers, who have differing references and experience.
- Moment 2 *"Sketches taking shape"*: consisting in further exchange on the project's orientations, and drawing up initial schemes. Students were still physically present and produced drawings and plans on paper. Students gradually make their sketches more concrete, adding measures and integrating the constraints of the plan given in the outline. Certain structure-giving choices appear in the paper sketches, such as arrows marked in red that indicate the intention to open up the school and facilitate people movement towards the interior of the building.
- Moment 3 "*Translating drawings and sketches into m^2 on the plan*": consisting in carrying out numerous calculations of space and levels, transforming drawings into concrete plans. Very detailed calculations (e.g. the height of a step) and difficulty in achieving them. Students were working at a distance, and produced unfinished plans within each level. Moment 3 makes it possible to pursue reflection around the project, using SketSha for the sketches and video-conferencing for oral exchanges. But the system, by offering a grill which allows the addition of a graphic scale to the sketches produced, very rapidly led the group to focus on detailed feasibility calculations for certain spaces (measuring a stairwell for example) to the detriment of the place and function of these elements in the project. As a result of this distance, the tool and the type of project that they have not yet mastered, numerous conflicts came to light between the project stakeholders. They had to adapt quickly to the conflict situation that arose, and aim for a more global vision of the project. This moment then led to another period centered on the general dimensions which had to be respected in the plan (*e.g.* the situation and dimensions of classrooms relative to the library and dining-room) rather than precise calculations of isolated elements.
- Moment 4 "*Abolishing m^2*": consisting in elaborating plans according to dimensional constraints, rather than strictly complying with criteria about m^2, with return to a more overall vision. Here, the students work at a distance and produce finalized plans for each level. This moment is when they return to the heart of the project, and takes the form of different sketches, more and more finalized according to level, and structured by the orientations defined during the design process.
- Moment 5 "*Reorganizing and finalizing project*": consisting in plans aligned with project orientations, space constraints examined, choices made in line with orientations. Students at a distance, produced presentation aids. At this point, groups retook possession of the project and were able to present it and make its guiding principles explicit, illustrating them with freehand drawings and SketSha sketches.

All through the construction of their projects, students practiced the method of enlarged design-possibility exploration, which they interpreted in their plans and sketches afterwards, introducing site and program constraints. Table 2 presents an extract of this exploration work.

The five moments that structured the collaborative design process bear witness to reorganizations

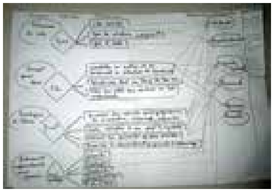
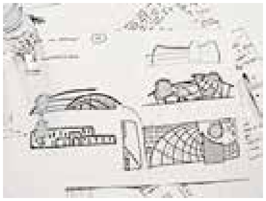
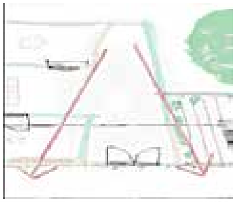
Moments		Situation and tools
Moment 1 – *Brainstorming*		Presence Paper/pencil
Moment 2 – *Sketches taking shape*		Presence Paper/pencil
Moment 3 – *Translating drawings and sketches into m² on the plan*		Presence Paper/pencil
Moment 4 – *Abolishing m²*		Distance SketSha – video conference
Moment 5 – *Reorganizing and finalizing project*		Distance SketSha – video conference
		

Table 1
Five moments structuring the design process.

Table 2
Enlarged method for exploring design possibilities for Echologia school project (extract)).

Objectives	Project Management contribution <=> End user contribution	Ownership Contribution <=> End user contribution	Solutions explored and selected
Accessibility	A school for everyone: -taking account of diversity -simplifying people-movement - respecting others	- For all disabled persons: wide corridors, large entrance, ease of access to all levels - Avoid multiplying means of access: long corridors, accessible toilets	Classrooms: arranged in blocks of 3 on 2 levels to create fluid people-movement - Room doors 1m wide for wheelchair access - Creating an identical, superposed access area on all floors Blocks: stairs/elevators, toilets and security post at an equal distance for everyone, everywhere, and close to each classroom. Ease of access: Facilitating people-movement towards the inside for everyone: all corridors in line for greater security and to avoid getting lost + accessibility for maintenance staff (disabled or not).

of collective activity, notably under the effect of teachers' interventions which guided or even reoriented the designers' work:

- Help with the initial definition of the school project: what school? For whom?
- Help with more detailed definition: a school for all; each future user's activity; accessibility;
- Reorientation: from detailed calculation of elements towards the overall meaning of the project: placing sketches in the plan, rather than precise calculations about the size of a staircase.

COLLABORATIVE DESIGN WHEN PHYSICALLY PRESENT, AND AT A DISTANCE

The work of the observers made it possible to follow the collaborative design process and identify the specific aspects of each situation and the role played by different artifacts (Belaitouche et al., 2012; Mateev et al., 2012).

Conflict. When physically present, confrontations relate to the main ideas of the school project and are expressed individually: everyone sets out their arguments and opens them up for debate in the group. New ideas gradually emerge and a consensus forms. When distance working, confrontations still relate to the project's main ideas but are expressed by one pair towards the other situated at a distance.

Withdrawal. When physically present, withdrawal takes the form of a less active role for one of the participants, which has several functions: indicating disagreement, or the wish to start another activity, related to the activity going on (e.g. making a drawing while the group progresses with producing ideas). This type of withdrawal turned out to be productive, as it makes it possible to share the drawings which fuel the ideas produced.

When distance working, withdrawal took the form of disappearing from the camera angle. This was less comprehensible and thus less productive in terms of taking the collective work forward.

Speaking and decision-making. When physically present, the flow of speech enables a certain proliferation of ideas. People occasionally talking over one another can be dealt with in the situation.

Decision-making happens before action: consensus is developed orally and is then translated into action.

When distance working, for reasons of comprehension, the pairs have to alternate speaking to each other in the form of questions and answers. Decision-making seems to follow the opposite movement from that observed when physically present: action takes place before agreement is reached, which can generate disagreement and even conflict within the collective. Actions carried out before oral agreement can include erasing part of a drawing or alternative propositions. They can serve a function of collegial decision-making, or the imposition of an idea.

Diversity of activities. The work of design is as much a matter of exchange and debating ideas as it is of drawings, sketches, tables and plans. When physically present these diverse activities – exchanging, writing, drawing – coexist without difficulty and mutually enrich one another: a quick sketch can be produced to support an idea. At a distance, on the other hand, it seems necessary to sequence activities, and this takes the form of a different way of organizing activity: expressing an idea, then writing or drawing – or developing a drawing and then explaining it.

Using artifacts. When physically present, designers make use of a wide variety of artifacts – sheets of paper, notebooks, pens, pencils, felt-tip pens, erasers – which enables them both to express numerous ideas and to withdraw in order to further develop an idea or drawing. It would appear that these artifacts serve a function of collaborative work just as much as individual, withdrawn work in the service of the collective work.

At a distance, work done on paper has been scanned and designs and drawings are available in digital form. Pens, erasers and felt-tip pens take the form of the SketSha software pen. This pen has several functions: it can write like a pen or felt-tip pen, erase, place and displace items on the plan. In addition there is only one pen, so that whichever designer happens to be holding it has considerable power to transform the project. Here too a certain sequentiallity can be observed in activities, as they develop step by step with the progress of exchanges and as the designers pass the SketSha pen from one to another.

CONCLUSION

In the first part of the paper we pointed out characteristics of design situations and the importance of collaboration, given multiple players: the importance of communication, the nature of tasks and how to distribute them, individual skills, negotiation procedures, conflict management and synchronization (Darses and Falzon, 1994). The ergonomic collaborative design workshop enabled our students to encounter complexity of design activity and collaboration. This innovative learning approach involves not only questions related to process and the "how-to" of design, but also questions related to the different types of contribution which have been articulated throughout the project, namely project management contribution, the ownership contribution and the End users point of view contribution.

The objective of the design methodology we proposed is to create unity of design and to allow diverse constraints to be expressed in an equivalent manner: constraints related to feasibility, and the will of stakeholders, go alongside those which deal with the planned end users. The End user point of view contribution plays a mediating role as it fertilizes different points of view, and makes it possible to anchor propositions in human-scale reality. It structures the whole project, from the first proliferation of ideas and drawings up to its finalization in the form of a sketch and/or plan.

Through being involved in the design process, observing and analyzing it, our students were able to realize that this sort of architectural design situation has its advantages and its limits. They nonetheless expressed the view that it would have been better to include architecture students too, so that they could contribute different expertise and points of view; this would have enriched their ideas, reflections and questionings about both about the project itself and about the collaboration process.

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Shape Grammars

Unambiguity

Difficulties in communicating shape grammar rules to a digital interpreter

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Abstract. *The rule editor of a parametric shape grammar interpreter is presented. The problems that arise are discussed along with their solutions.*
Keywords. *Shape grammar; parametric shape grammar editor; implementation.*

INTRODUCTION

Shape grammar implementations, in theory and praxis, have received increasing attention over the last years. Recent projects have been introduced by Yazar and Colakoglu (2007), Trescak et al. (2009), Yue et al. (2009), Keles et al. (2010; 2012), Jowers and Earl (2011) and Grasl (2012). Each project offers some solutions to the general problem, but few implement or describe rule editing capabilities. A complete shape grammar interpreter should support emergence, parametric rules and rule editing via a graphical editor. Here the results of such an effort (Grasl and Economou, forthcoming) are described with a focus on the peculiarities of the parametric rule editor.

In order to implement a rule editor for a shape grammar interpreter several difficulties have to be overcome. Mark Tapia (1999) already introduced some ideas concerning the user interface, most of which still hold today. However, the editor described by Tapia did not support parametric rules.

Although ambiguity is sometimes seen as a strength of shape grammars (Stiny, 2006), it is not during rule definition that it should come into play. Here unambiguity is essential. This is perhaps the dilemma of trying to implement shape grammars with binary devices. In the context of a rule editor ambiguity will result in little more than serendipity. Despite the successes of serendipity, here we will try to restrict it to a minimum. Rather it is during the match finding process, while decomposing a shape into its constituent parts, that ambiguity has its place.

As simple as many rules may seem to the human mind when drawn on paper and explained by an accompanying text, it is quite a different matter if a digital computer is the entity trying to understand. It is fantastic how many details the human mind can overlook unbothered, how many blanks are filled in on the fly in order to understand a rule.

Of course if one were to sit down and describe a rule in computer code some ambiguities might fall away, most likely though it will take several attempts until the desired result is achieved. In any case this is not the desired solution, rather the designer should be able to communicate with the computer in a more intuitive language, that of the drawn shape. This is difficult enough for a non-parametric, or rigid, shape, but once parametric matching is allowed things become all the more complicated.

EDITOR

Conventions

Like Tapia proposed, it has turned out that drawing the left hand side (LHS) and the right hand side (RHS) on top of each other, rather than on their respective sides of an arrow, is advantageous.

If for example rule 1 (Figure 1) cannot be described by absolute changes, like:

'Move the square 2 units to the right and 2 units up'

but rather has to be captured in relative terms like:

'Translate the square by the vector $\overline{AC}/2$'

it is clearer if they are overlaid. Clearly all the parameters used for such a description have to be derived from the LHS, since the RHS does not exist at the time of rule application. In a sense the RHS has to be rigged onto the LHS and overlaying makes this clearer.

Colours are according to what is used for construction documents of a renovation project. The LHS is drawn in black, the colour of existing objects that are not altered. New objects, in our case the RHS, are drawn in red. Objects that are deleted are yellow. Figures in this paper follow a slightly different convention: Existing, unaltered lines are dark grey, new lines are black, deleted lines are not used, but could be light grey.

Rule interpretation

Although it was attempted to keep the interface as graphical as possible, it did turn out that making a few categorisations via drop-down lists simplifies the interpretation of the rule.

Not all rules can be handled in the same way. In this respect the schemas introduced by Stiny (2006) have proven to nicely organise the rules. Of course the general schema

$a \rightarrow b$

has to be covered. In addition a distinction was made for rules that use transformations only

$a \rightarrow t(a)$

This distinction is a necessity, to deal with rules similar to rule 2 (Figure 2a). Rule 2 is ambiguous in

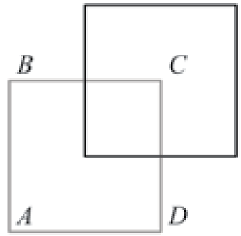

Figure 1
Rule 1: Copy and translate a square along half its diagonal.

the sense that its verbal description could for example be:

'Rotate a square by 45° and then scale the result by $1/\sqrt{2}$'

or

'Inscribe into the square ABCD a second square EFGH such that $\overline{AE} = \overline{EB}$, $\overline{BF} = \overline{FC}$, $\overline{CG} = \overline{GD}$, $\overline{DH} = \overline{HA}$'

For a normal rule it does matter which description is selected. If however the rule is parametric, in the sense that it can be applied not only to squares, but also to rectangles and other quadrilaterals, the difference is meaningful. If the rules

'Rotate a quadrilateral by 45° and then scale the result by $1/\sqrt{2}$'

or

'Inscribe into the quadrilateral ABCD a second quadrilateral EFGH such that $\overline{AE} = \overline{EB}$, $\overline{BF} = \overline{FC}$, $\overline{CG} = \overline{GD}$, $\overline{DH} = \overline{HA}$'

are applied to a rectangle the outcome will be very different (Figure 2b).

Additionally a distinction is made for rules that leave the LHS unaltered

$a \rightarrow a + b$

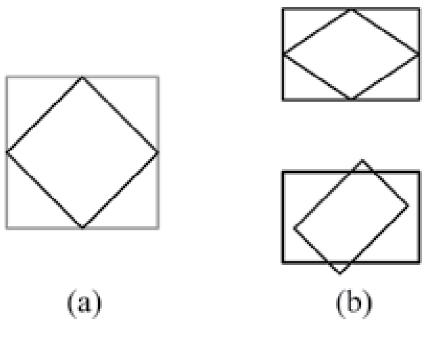

Figure 2
(a) The parametric rule 2 and (b) varying results depending on its interpretation.

Table 1
Possible mappings and their meaning.

	Position	Length	Angle & Ratio	Parallelism	Cross ratio	Neighbourliness
Identity	•	•	•	•	•	•
Isometry		•	•	•	•	•
Similarity			•	•	•	•
Topology						•

and
$a \rightarrow a + t(a)$
respectively. The first two schemas could also deal with these cases. It is more a matter of convenience to prevent having to redraw the LHS.

The mapping used for match finding is another category the designer has to select. Essentially the permissible transformations are defined. Rules are assigned one of four mappings: Identity, Isometry, Similarity and Topology (Table 1).

The first, 'Identity' is included for completeness sake. Scale, rotation and position must match exactly. This mapping is normally not used for shape grammars, but it is not unthinkable.

'Isometry' is a mapping where rotation and translation is allowed. Shapes must have the same lengths and angles.

'Similarity' allows for scaling in addition to rotation and translation. This is the default mode, as it is also the most common method of matching shape rules.

'Topology' requires only the structure, the neighbourliness, to match. It is the most flexible mapping and the basis for truly parametric rules.

CONSTRAINTS

Mapping constraints

Rules of all mappings except for 'Topology' are triangulated over the set of vertices; this is for internal use only and is not displayed to the designer. The triangulation ties together disjoint shapes (see rule 3; Figure 3) and helps to avoid having to deal with angles and trigonometric functions. The triangles are then constrained according to the selected mapping as shown in Table 2.

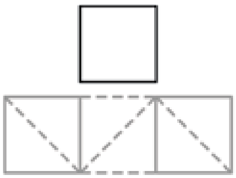

Figure 3
Rule 3 and its triangulation that is generated for some of the mappings.

Symmetry constraints

Finding a match in all its symmetric variations is a task assigned to the shape grammar engine rather than the editor, and is described elsewhere (Grasl and Economou, forthcoming). Sometimes however too many variations of a match can be returned. This is the case if the rule itself exhibits some symmetry and thus cancels out some of the prospective matches. Here the editor can help by detecting such symmetries of the rule and by adding appropriate constraints to the description. For this purpose an algorithm as described by Wolter et al. (1985) was implemented.

For example, rule 1 (Figure 1) shows a rule that has mirror symmetry through [AB]. Normally the engine would return each square in eight variations, the eight isometries of the square. In case of rule 1 however each left turning variation will have one right turning variation that will result in the same shape. Here a constraint on rotation is added by the editor
$(\overline{AB} \times \overline{AC}) \cdot \bar{z} > 0$
restricting the cross product of two vectors to a positive number.

Manual constraints

In addition to these automatic constraints rules can also be constrained manually. The web based implementation does not allow for constraints to be defined graphically, instead each vertex is marked with an alphanumeric value; these identifiers are then used to formulate constraints mathematically.

Topology	No automatic constraints.
Similarity	The proportions of the edges of the triangulation are constrained.
Isometry	In addition to the proportions one length is constrained to an absolute value.
Identity	The coordinates of all vertices are constrained.

Table 2
The constraints that are added automatically depend on the chosen mapping.

Manual constraints are important to model specific requirements that cannot be covered by a mapping alone. If for example a rule should be applicable to rectangles of all proportions, then the topology mapping hast to be used in combination with geometric constraints restricting a quadrilateral to a rectangle.

CONCLUSION

Implementing a general parametric shape grammar interpreter is not an easy task. Once it is achieved the question arises of how to feed the interpreter with rules. Of course the rules could be formulated directly in the underlying representation used by the interpreter. In the case at hand this would mean describing the rules as graph grammar rules in the description language provided by the graph grammar engine. While this is indeed a flexible option, and possibly the best approach for some very specific rules, in general it is desirable to be able to specify rules graphically.

The approach presented here builds on the underlying graph representation of shapes. Nevertheless most of the findings should be application to other implementations as well.

Defining the required mapping is not essential, since the same effect can be achieved by manually adding constraints. However, this is tedious and more often than not a mapping will suffice.

Manual constraints are of course an absolute necessity for a parametric shape grammar interpreter. Visual constraint definition would be nice, but formula based constraints have proven to be a good and flexible solution. Visual constraints can be added fairly easily if the editor is implemented in a CAD environment that supports such constraints.

Treating rules of the schemas $a \rightarrow b$ and $a \rightarrow t(a)$ differently could perhaps be avoided if complex rule definitions based on constructive geometry are possible. Again things are simplified by offering this additional possibility.

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Customized Cork Façade

A generative design process based on shape grammars

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Abstract. *The propose paper presents an ongoing research which main goal is to use cork in a customized modular façade system. Cork is used due to its ecological value, renewable characteristic, insulation properties and aesthetic value. The modular system design is bio-inspired in the microscopic cork pattern and the study aims at reproducing in the façade some of the natural characteristics that enable cork to be suitable for the function it plays in construction. Façades are design by a generative design process based on a parametric shape grammar which encodes shape rules and an algorithm to guide the generation. The developed cork modules are part of a back-ventilated façade system which is assembled upon a substructure that reproduces the cork cell structure and enables both the assemblage of the modules to the support wall and the connection between them.*
Keywords. *Shape grammar; generative design; cork; façade; digital fabrication.*

INTRODUCTION

The use of a generative design system enable the generation of multiple solutions based on different scenarios and requirements that would introduce different variables to the system.

Recently both the fabrication and the design process in Architecture are being questioned by the use of digital technologies for the promotion of more efficient buildings. Requirements such as good structural or thermal performance and customization are the cause of the arising of new generative processes.

Design assisted by generative processes such as shape grammars allows the customization and optimization of solutions by manipulating parameters. Combining these processes with new digital fabrication techniques enable new products to be design which are customized, respond to pre-defined requirements and still maintain production costs.

However architectural quality is not absolutely measurable, there are some specific qualities that are well measurable. Energy efficiency is one of those qualities. The use of materials with good insulation values and the optimization of window openings according to the site insulation characteristics will improve a specific type of building quality.

Kroes et al. (2008) state that the emphasis upon building performance brings the architecture world much closer to engineering design. According to Gruber (2011) the quality of a final project is defined by the quality of investigation conducted in the important stages of design. The challenge proposed is to combine the expanded vision of the architect with the fulfillment of specific variables using also quantitative criteria rather than just the qualitative criteria typically used in the architectural work.

Gruber (2011: 49) states that "in architecture, problems in design often affect many levels of the project, and often they are difficult to define." As a consequence several tools are too specific to be use in architectural problems since they are usually not looking to all the levels of the problem but only to some of them. However, these tools may be suitable to solve specific design tasks and questions (Gruber 2011: 49).

DESIGN PROBLEM AND GOALS

The problem this research wishes to address is how to design a system to generate customizable façades with a natural material as cork without becoming to expensive.

The main goals of this research are:

- Use pure cork agglomerate as a building coating material and explore its thermal isolation and aesthetics potential;
- Define a generative design process bio-inspired in cork composition based on shape grammars which meets a visual-performative language;
- Define a modular cork façade system which meets a variety of thermal requirements considering different contexts;
- Define a substructure to support the cork modules in a back-ventilated façade system.

Besides those, other motives were to explore architecture performance and mass-customization, materials and construction technologies as well as CAD/CAM digital technologies.

FRAMEWORK

Cork pattern, materiality and visual characteristics

Cork is a natural, renewable and environmental-friendly product that comes from the renewable bark of the Cork Oak. Natural cork agglomerate is used in this research because of its excellent thermal isolation properties and because it has great properties to be used at exterior façades becoming lighter or darker according to weather conditions. Both natural and black agglomerate cork is used in construction because of its very good performance as acoustic, thermal and vibration insulation (Gil 1996). These materials are available in sheets or boards with variable thickness and their manufactured is mainly done with "granulates from cork stripping (virgin cork) obtained from pruned branches of the cork oak tree" (Gil 1996).

The microscopic pattern of cork (Figure 1) was used as an inspiration pattern for the development of the façade modular design with the aim of mimetizing Mother Nature's harmony by using similar logics and principles of organization. Through Hooke's observations cork was found to be made of cavities (cells) full with air which enable the material to float, be firm and yet compress under force. However there are also structures around the air cavities which support the material (Humes s.d.). This meticulous natural design has inspired and lead to differ-

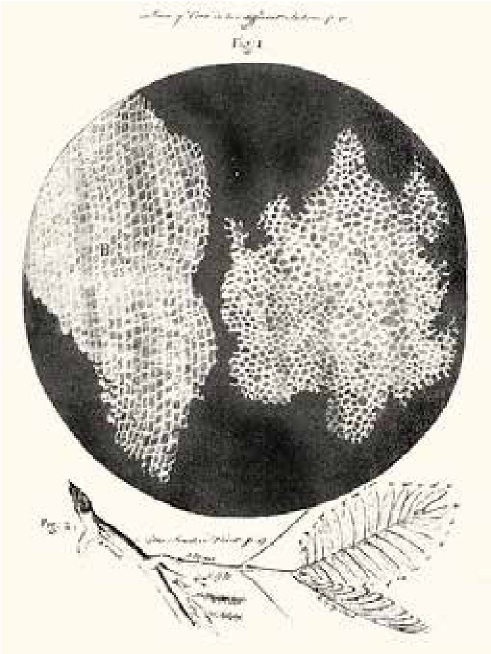

Figure 1
Drawing of the structure of cork as it appeared under the microscope to Robert Hooke (http://en.wikipedia.org/wiki/Robert_Hooke).

ent patterns in the proposed design.

The choice of materials in architecture have an immense effect on the behavior of the people using a space because of their functional performance and their image, brand, identity feel and the atmosphere they give to the space (Gagg 2012). Beside the enunciated measurable advantages of cork regarding its technical specifications and performance, its aesthetic may give a sense of warm and comfort to users which we want to explore when using it in new ways.

Generative design and shape grammar

Recently architecture and biology are overlapping fields of research by exploring different methodologies of translating knowledge gained from nature into technical solutions (Gruber 2011). Generative processes of design in architecture are being studied and the arising of emergent shapes represent a current research line both in architecture and other areas such as computation sciences and biology. Emergent patterns may be observed, recognized and extracted from natural patterns and mathematically explained through algorithms or parametric shape grammars. The goal is the generation of efficient architectural structures inspired by the logics of nature performance. Bio-inspired design can be used in architecture in different ways, from the use of stylistic and aesthetic nature's logic to the use of nature's performance potentials as the ability to use in an efficient way the solar radiation.

Shape grammars are generative processes developed since the 70s by George Stiny and James Gips (1971). They are "algorithmic systems for creating and understanding designs directly through computations with shapes, rather than indirectly through computations with text or symbols." (Knight 2000)

The generation process enabled by shape grammars allows for multiple designs to be generated, based on a single language but determined by different choices (Eloy and Duarte 2012). The use of a shape grammar enables to encode both the shape rules that explore the visual properties of the pattern (bi and tri-dimensional) and the constraints needed to design a façade. Shape grammar languages do not look for one solution to a given problem but for multiple solutions based on the same set of rules or criteria (Eloy 2012). In shape grammars, rules are used as mechanisms for generating designs.

DESIGN GENERATION

Phase 1: Cork as pattern

The process started by the use of the microscopy image of cork and with the identification of its pattern by visual analysis. From that stage a vector drawing was done over the cork image and a triangular module emerged as the simplest shape and the one which enabled the most infilling diversity.

During this phase different shape approaches have been followed resulting in different shape vocabularies and shape rules. It was considered since the beginning that the modular façade construction should consider two types and stages of work: a first stage involving industrial fabrication of the base modular pieces and a second stage involving a customized design and fabrication by digital tools on those pieces. These criteria lead us to develop the design grammar by using the simplest shape possible to the base modular piece that will be repeated. This triangle is use both for the surface pattern of cork modules and for the load bearing façade substructure inspired in the cork's air cells and edge structure discovered by Hooke.

It was our goal to explore the visual complexity dynamic of the microscopic pattern of cork and use it dynamically in a building façade to stress cavities (windows), dark/light or shades (material thickness) and strength (support structure).

Phase 2: Encoding the rules

The inference of shape rules was done by hand after analyzing the microscopic patterns of cork. In the first stage the geometric shapes were identified through the process of isolating possible combinations. The goal was that the modular shapes could be easily fabricated and assembled and simultaneously would enable the generation of multiple combinations of design. This was done by using a triangle as the base module. The adding rules that introduces a second triangle in the façade uses the left part of the rule and adds a new triangle by mirroring through one of its sides (rule 2 and rule 3, Figure 2).

After developing rules that fill the façade with the base module the second stage was the definition of the shape geometry inside the triangle. In between side by side triangles, these inside geometry should generate the polygons that are characteristic from the cork microscopic pattern. To both generate polygons and make them dynamically different from each others, a parametric rule was added to the shape rules 4 and 5 in Figure 2.

The third stage was the definition of several shape rules which encoded the thickness possibilities as well as rule conditions (Figure 2, rules 6 to 10e).

These rules allow the use of Euclidean transformations as symmetry, rotation and translation to the generation of different designs.

The developed rules obey to two main criteria: i) thickness differs with solar orientation of the facade; ii) one base module has always two different thicknesses.

Phase 3: Design generation

The generation begins in a vertex of the façade and the use of shape rules allows the all surface to be filled of modules. Rule's application follows criteria like: different thicknesses in north/south and east/west facades; diversity in the thickness in adjacent modules; non-repetition in adjacent modules; higher thickness in more exposed places of the façade; windows openings/voids position.

Figure 3 show a possible layout of façade that was generated through the developed shape grammar.

The coating cork modules are part of a back-ventilated façade system which is assembled upon a triangular substructure that disappears from the exterior face of the coating to the back in order to support it. This metal substructure, located at the borders of the modules, enables both the assemblage of the modules to the support wall and the connection between them.

Phase 4: Prototype

The final phase will be the test of the customized cork façade in 1/2 scale models by using CNC digital fabrication techniques. Two possibilities will be tested in triangular pieces, cork with 20cm of thickness and two layers of different cork with a total thickness of 20cm. The goal is to test the assemblage of the modules both between them and to the metal substructure and, if necessary, to go back and review unresolved situations detected during the fabrication.

CONCLUSIONS

At this point of research we can preliminary conclude that it is possible to interpret and infer patterns of nature using a shape grammar and that we can use this grammar to generate similar patterns.

The proposed design is bio-inspired by the microscopic structure of natural cork. The understanding of this pattern led us to re-interpret it and design the proposed façade in a two layer system considering the loadbearing structure (edges) and the infill/coating material (cells).

The use of a modular cork façade system which can be generated by a generative process allows a more rational design process since it enables multiple design to be developed but establishing modular standards that has to be obey.

By addressing an experimental issue this research helped to understand the potentials of relating bio-inspired design, generative process and digital fabrication techniques. With the use of these technologies more sustainable structures can be obtained which will meet nowadays and future requirements.

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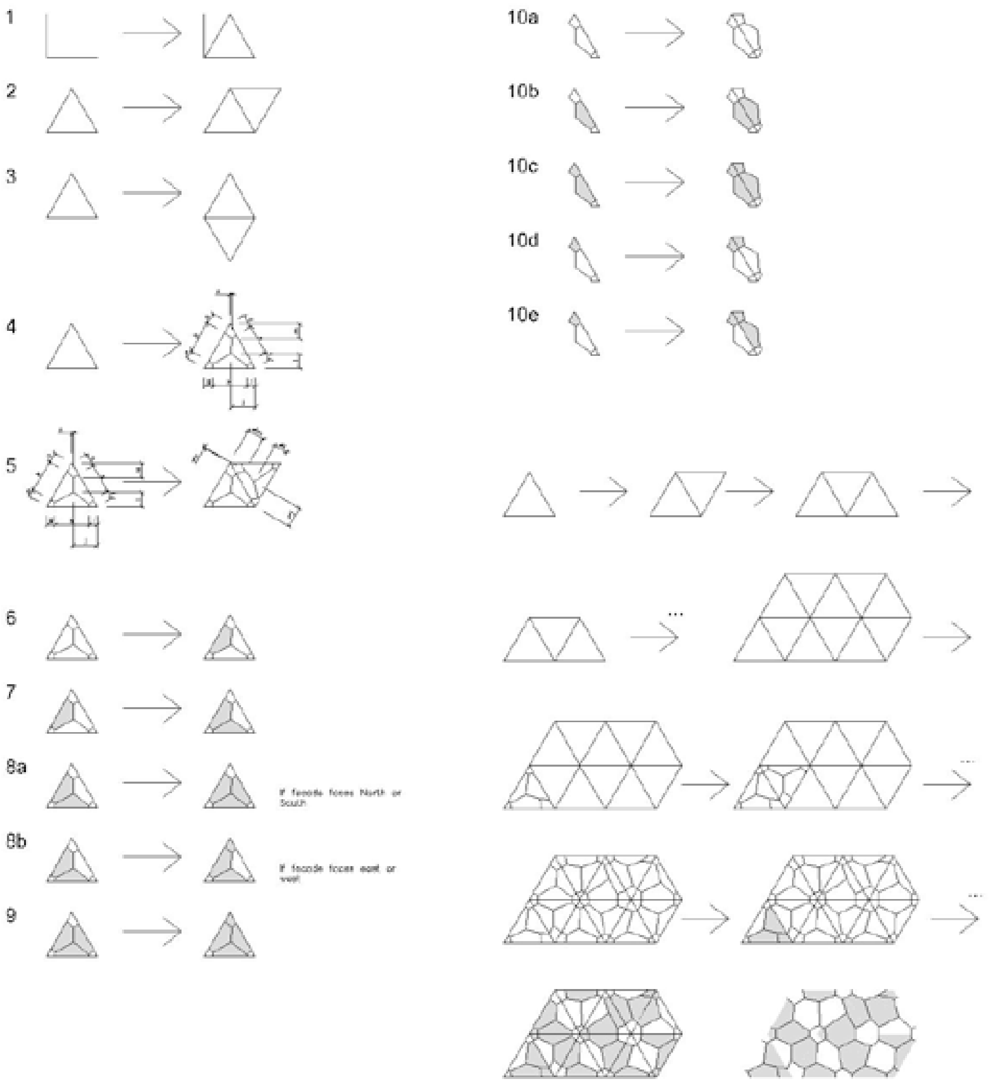
Figure 2
Simplified shape rules and sample derivation.



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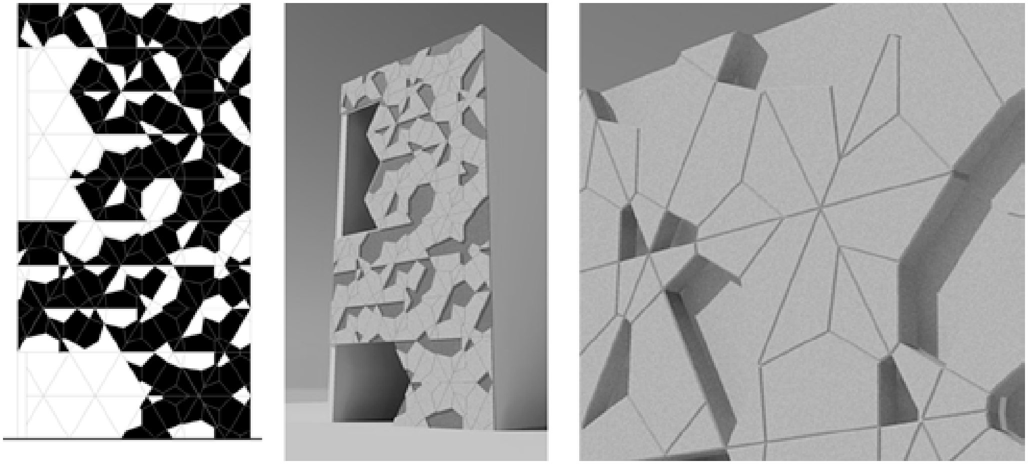

Figure 3
Examples of one final design of the customized cork system façade, with two different types of cork or just one.

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A Generative Approach towards Performance-Based Design

Using a shape grammar implementation

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Abstract. *Due to a growing number of regulations and standards, building performance becomes equally important as traditional design drivers. Therefore, it is necessary to quickly explore design alternatives that meet these performance requirements. To support this complex design task, a rule-based design system is proposed that is founded on a shape grammar. This paper describes a graph-based implementation of this shape grammar that allows subshape detection, parametric rules and attributed shapes. The implementation described in this paper forms the basis to further investigate to what extent rule-based design systems can support a generative approach towards performance-based design.*
Keywords. *Shape grammar, evolutionary algorithm, performance-based design, implementation, generative design.*

INTRODUCTION

A growing number of regulations and standards to which nowadays buildings have to comply, has put design performance back on the architectural agenda. This has led to the emergence of a performance-oriented architectural design paradigm in which building performance (regarding sustainability, safety, accessibility, comfort, etc.) becomes equally important as traditional design drivers such as functionality, history or aesthetics (Kalay, 1999). In contrast to the traditional design process, in which performance issues are often dealt with in a post-engineering optimization phase, the performance-based design process takes into account the performance requirements in an early design phase. Recent technologic advances in computational design systems allow the integration of performance requirements and have led to an increased productivity of the design process (Petersen et al., 2010). More specifically, added programming possibilities allow the continuous generation and evaluation of parametric variations in order to select (sub-)optimal design solutions (Strobbe et al., 2012).

Such CAD-systems are often founded on a geometric representation of the design. However, the current increased emphasis on building performance in architectural design starts to question this central role of geometry in CAD. The designer has to work within the constraints of government rules and regulations to accomplish a good compromise from a wide range of design solutions. Such constraints are diverse in nature and often difficult to translate into a graphical or geometric form. Therefore, parametric modeling so far allows the generation of quite restricted geometric variations in the model. Furthermore, a geometric representation of design is inappropriate from a computational and automat-

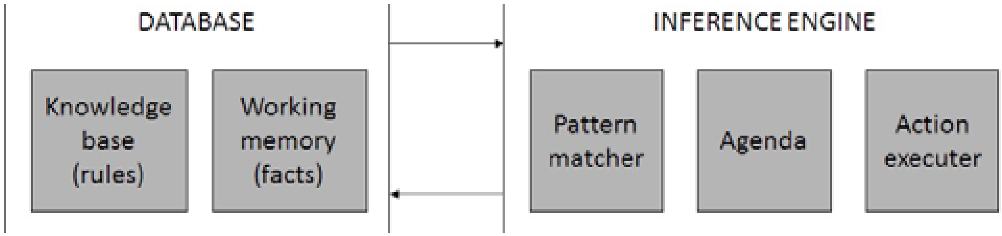

Figure 1
The rule production system consisting of the database and the inference engine.

ic reasoning point of view, as it is computationally expensive to identify features to be computed from a set-theoretic representation of a geometric object.

More appropriate in the context of supporting the design process, is the combination of a geometric representation and its rule-based representation. This allows the representation of the design through a sequence of design rules that preserve design information that otherwise has to be reconstructed. This representation is more suitable for computer implementation and can allow both (1) automated reasoning on the design and (2) the generation of a design grammar (i.e. family of designs) that extends restricted parametric variations. These functionalities can support the designer in different types of problem-solving activities by generating alternative or even sub-optimal design solutions within a grammatical paradigm.

Our research investigates to what extent rule-based design systems can provide essential support in the core design activities of architectural designers. This paper describes an implementation of such a rule-based design system, founded on a graph-based shape grammar. One possible graph-based design representation is described and it is discussed how a grammar of designs can be generated through the application of design rules.

SHAPE GRAMMAR IMPLEMENTATION

Rule production system

A rule-based design system founds on the collection and management of design 'knowledge' in form of rules, as is the case in rule production systems. A rule production system generally consists of a database and an inference engine (Figure 1). The database contains all the design knowledge in form or production rules (knowledge base), together with information about the current state or knowledge (working memory). A production rule is modeled as a transition between a 'before' and 'after' state. The left-hand side of the production rule describes all the preconditions that need to be satisfied, while the right-hand side describes the action of the rule execution. If the production rule's precondition matches the current state of the working memory, the production's action is executed.

The inference engine starts with the facts in the working memory and uses the matched production rules to update, remove or add new knowledge to the working memory. In order to select and execute the production rules, the inference engine contains a pattern matcher, agenda and action executer. Firstly, the pattern matcher uses an algorithm to collect production rules of which the preconditions are satisfied with the facts in the working memory. The collection of rules resulting from the matching algorithm is called the conflict set. Secondly, the agenda determines the resolution strategy of the conflict set, for example according to priorities assigned to the rules or according to the order in which the rules were written. Thirdly, the action executer performs the production rule's action and removes it from the agenda. This process is continuously iterated, resulting in different production system derivations.

Shape grammar

The use of production systems to provide some form of artificial intelligence is found useful in several scientific domains. In the domain of architectural design, shape grammars (Stiny et al., 1972), a class of production systems that generates geometric shapes, are used to capture design knowledge into shape rules. Shape grammars define a rule-based formalism to represent visual thinking and to handle ambiguities that are characteristic of architectural design. A key concept in the shape grammar formalism is the embedding relation that lies at the basis of handling ambiguities (Stiny, 2006). Embedding allows the recognition of emergent (sub)shapes that are not predefined in the shape grammar, but emerge from shapes generated by rule applications. Once a rule is applied, all the shape parts fuse and the new shape needs to be 'reframed' in order to proceed with the rule application. Therefore, embedding allows an open-ended way to generate multiple design derivations and to explore a design solution space towards novel or unexpected areas.

One of the current challenges is the computer implementation of shape grammars. Gips (1999) provides an overview of previous research efforts on shape grammar implementations and describes several issues and obstacles, of which most of them are still valid to date. These obstacles include the lack of parametric shape support and the subshape detection problem. The support of parametric shapes involves parameterized shape rules. The subshape detection problem is to determine whether a shape contains a specific subshape. The main challenge of the computer implementation is thus to find an underlying representation that is both able to support the visual nature of shape grammars and amenable to computer interpretation. In the remainder of this paper, an approach is described that uses a graph-based representation of the design (facts) and design rules, together with a graph transformation system (inference engine).

GRAPH-BASED REPRESENTATION

The graph-based representation of a design consists of pairwise relations between objects. In the domain of architectural design, graphs are mainly used to model topological configurations of architectural spaces or to describe geometric data structures. As an example of the former approach, Grasl (2012) describes a graph representation of a Palladian-style villa that consists of an adjacency graph for the grid underlying the design. While this approach is mainly useful to implement specific graph representations, the latter approach is more suitable for general implementations. For example, Heisserman (1994) introduces a boundary graph to represent three-dimensional solids. The graph nodes represent topological elements (such as vertex, edge, face, etc.) and the arcs represent the adjacencies between the elements. Geometric information (coordinates) is associated with each vertex node as an attribute. The boundary graph is based on the generalized split-edge data structure that is capable to store adjacency information of geometric objects. Heisserman's approach has been further investigated in several research efforts, for example the GRAMATICA three-dimensional interpreter (Correia et al., 2012) or the web-based implementation GRAPE (Grasl et al., 2011).

The main advantage of the graph-based implementation of shape grammars is that both parametric shape rules and subshape detection are supported (Grasl et al., 2011). Firstly, the ability to support parametric shape rules is caused by the topological nature of graphs. A graph can represent multiple geometric shape variations. For example, the graph representation of all quadrilateral shapes (square, rectangle, trapezoid, etc.) are isomorphic or topologically identical. Secondly, the ability to support subshape detection is based on the subgraph isomorphism problem (Ullmann, 1976). Subgraph isomorphism involves determining whether a graph contains a subgraph that is isomorphic to a given graph. While the subgraph isomorphism problem is proven to be NP-complete, Grasl et al. (2011) demonstrate that practical solutions can nevertheless be created. Thirdly, attributed graphs also contain non-topological information that is described in the form of attributes.

Approach

Based on Heisserman's approach (1994), the attrib-

Node Type	*Attributes*	*Type*
Vertex	ID	String
	x, y, z	Float
Edge	ID	String
	length	Float
Face	ID	String

Table 1
Node types and their attributes.

uted graph represents (geometric) objects as nodes, and relations between these objects as directed arcs. Several node types are distinguished that represent different objects (vertices, edges and faces) (Table 1). This approach can be extended to an unlimited number of nodes that represent different objects (for example: "*Solid*", "*Wall*", "*Door*", "*Window*", etc.). Similarly, several arc types are distinguished that represent different relations between the geometric objects, for example: "*hasVertex*", "*hasEdge*", etc. In addition, several attributes are associated with the graph objects in order to store non-topological information: unique ID's are associated with all nodes, coordinate geometry is associated with vertex nodes, etc.

The graph representation contains only topological information of the shape, which allows the support of parametric shapes. Additional attribute information (e.g. coordinate geometry) is needed to restrict the parametric shapes to specific geometric shapes. Therefore, an attributed graph-based representation ensures a unique mapping between the shape and the graph. An example of the graph representation of a geometric line object is given in Figure 2. The graph consists of two vertex nodes (white), one edge node (black), and two directed arcs from the edge node to the vertex nodes. The line is considered parametric, if the coordinate geometry attributes contain parametric values.

GRAPH RULES

Parallel to the graph-based representation of the design, the rule set can also be described using the same representation. This graph-based rule representation enables the collection and management of design knowledge with a far greater expressive power than pure data. Once a rule is described, it can be applied in different environments using an inference engine. Graph rules are described as a transition between two graphs, following a typical IF-THEN statement. The left-hand side of the graph rule describes the graph that needs to be matched to the host graph, together with additional conditional statements. These conditions include attribute conditions and negative application conditions (NAC). Attribute conditions define restrictions on the attributes of the graph, while NACs specify requirements for non-existence of sub matches. The right-hand side describes the transformation of the host graph. This graph transformation includes deleting or manipulating existing graph objects, creating new objects, and also performing computations on the object attributes.

As an example, the graph-based representation of a shape rule that generates a Koch curve is displayed in Figure 3. The Koch curve is a mathematical fractal curve that is constructed by recursively replacing a line segment with an equilateral triangle. Therefore, the left-hand side of the rule represents a line segment and the right-hand side represents a graph with both modified and new graph ob-

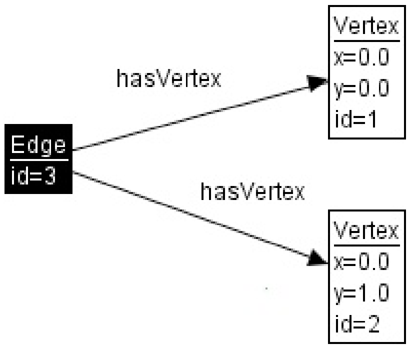

Figure 2
Graph representation of a non-parametric line object.

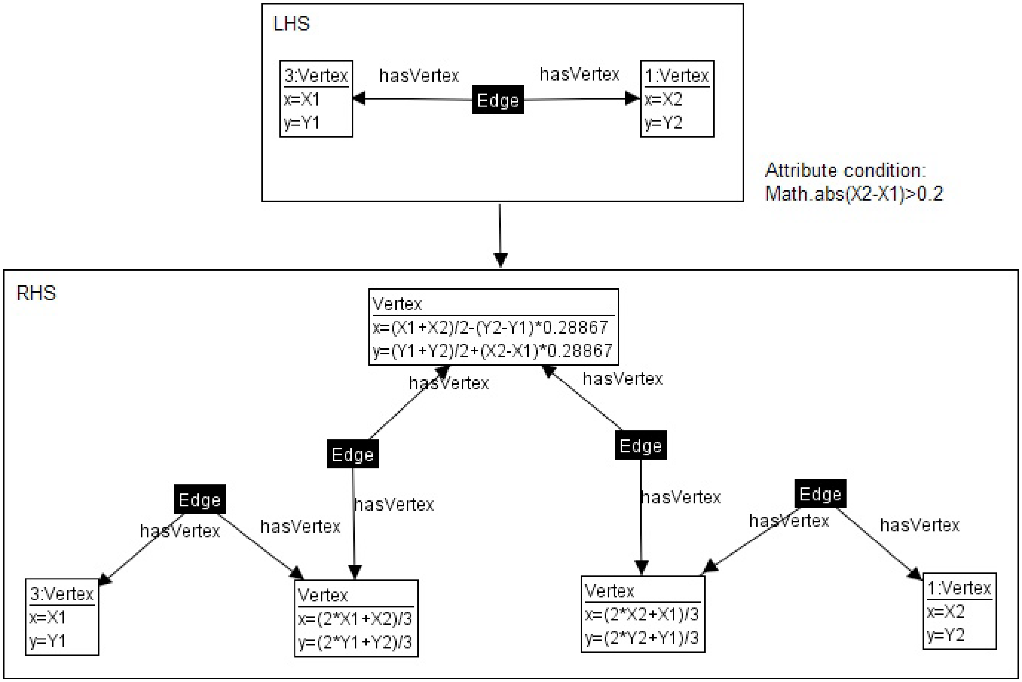

Figure 3
Graph-based representation of a shape rule that generates a Koch curve.

jects. The attributes of the new nodes are defined as expressions that take into account the attribute context of the matched host graph *(X1, Y1, X2, Y2)*. Furthermore, an additional attribute condition is implied in order to ensure a minimum length of the generated line segments.

GRAPH TRANSFORMATION SYSTEM

A graph transformation system is used to allow the stepwise application of graph rules on the original host graph. Among others, AGG is a general graph transformation system written in JAVA (Rudolf and Taentzer, 1998). Rule application is performed by matching the left-hand side of a graph rule to the host graph and replacing it using a preservation morphism. The AGG system solves the problem of graph matching, i.e. the subgraph isomorphism problem, as a constraint satisfaction problem (CSP). As indicated previously, this feature enables the detection of subshapes, which is an important challenge for shape grammar implementations. Also, the matching conditions are evaluated in order to recognize specific shape features. The preservation morphism describes the mappings of the objects of one graph to those of another, using tags to indicate the mapped objects. If multiple matches are found, all possible morphisms are calculated and stored. The selection of the morphism can happen non-deterministically or using a user-defined sequence (for example through priorities assigned with the rules). The user can go back and forth in this transformation process, and generate multiple alternatives.

In the following example, the initial line shape that is described in Figure 2 and the Koch rule that is described in Figure 3 are used to generate shape grammar transformations. Figure 4 shows several graph transformation steps in the generation process (step 0, 1, 2 and 10). Rule matching and selec-

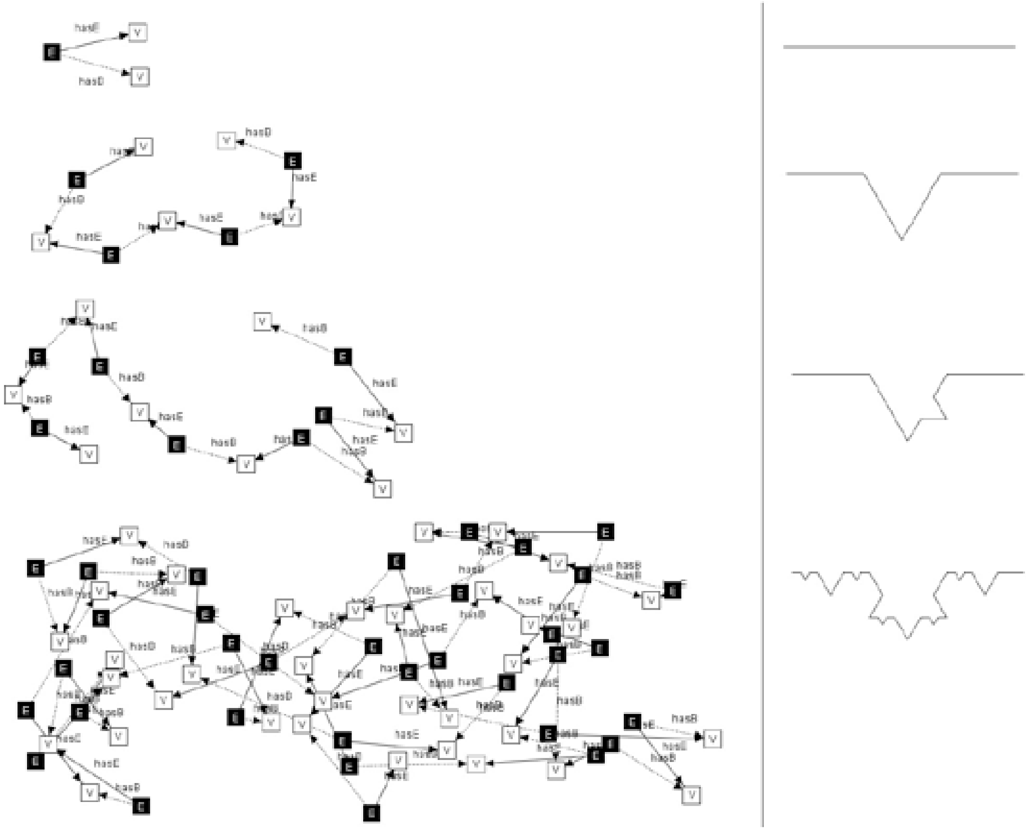

Figure 4
Graph-based (left) and shape (right) representation of several graph transformation steps (0, 1, 2, 10).

tion is performed non-deterministically, in order to allow a depth-first design exploration process.

CONCLUSION AND FUTURE RESEARCH

This paper describes the implementation of a rule-based design system using a graph-based representation of a shape grammar. An approach is proposed that allows subshape detection, parametric shape rules and attributed graph objects. Therefore, it is possible to quickly explore design alternatives that extend parametric variations. A simple case study has demonstrated the feasibility of this approach, however, a more complex design context is needed in order to test the practical value of this approach. In the case of performance-based design, further research is needed to determine which domain knowledge can be incorporated in the rules and whether heuristics are needed to go back and forth in the transformation process. Therefore, the work demonstrated in this paper forms the basis to further investigate to what extent rule-based design systems can provide support in the design process.

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Tableware Shape Grammar

Towards mass customization of ceramic tableware

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Abstract. *Mass customization is pointed as a means of improving a company's competitiveness, which is an essential trait in Europe's economic situation of today. This paper reports a mockup implementation of the mass customization paradigm to ceramic tableware design, through the use of shape grammars, parametric modelling and rapid prototyping. Focus is emphasized on the initial development of a parametric shape grammar as a design system, operating on curved surfaces and solids. Mapping operations are suggested for dealing with the formal complexity of these shapes. This initial academic experiment poses as a first step into the development of a mass customization system that is expected to meet industry standards.*
Keywords. *Mass customization; ceramic tableware; generative design; shape grammars; rapid prototyping.*

INTRODUCTION

Research is currently being developed towards the application of the mass customization paradigm to the design and production of ceramic tableware. The experience documented in this paper represents a first mockup of the framework necessary for the implementation of such paradigm. The ultimate objective is that end users can create their own, highly customized, tableware set.

According to Duarte (2008), the implementation of a mass customization system implies development on three fronts: a design system that encapsulates the stylistic rules of tableware elements, generating the corresponding digital models; a production system that allows to automatically materialize those models into usable tableware elements; and a computational system that implements the design system and articulates it with the production system.

According to Pine (1993), mass customization can improve a company's competitiveness, allowing it to offer differentiated products to its customers. This research is thus intended to be applied to an industrial context, through collaboration with a local ceramics company.

Methodology

A small scale implementation of the mass customization paradigm was tested as an exercise, in a semester long course about shape grammars. In this exercise, the shape grammar apparatus, invented by Stiny and Gips (1972), was used as a design system, encoding the rules for the shape generation of tableware elements into a parametric shape grammar. This paper will focus mainly on this design system.

Subsequently, parametric models corresponding to derivations of the shape grammar were implemented using the visual programming interface Grasshopper. The implemented system allows the user to combine shape rules and manipulate its parameters, generating derivations of the tableware elements and the corresponding digital models.

Finally, these digital models could then be automatically produced using powder-based 3D printing equipment.

Application of shape grammars to three-dimensional curved shapes

Although the original shape grammar has been developed for straight line shapes (Stiny, 1980), some authors have used this tool to work with curved shapes, which are predominant in tableware design.

Knight (1980) developed a shape grammar on Hepplewhite-style chair-back designs. While deriving the chair-back shape mostly in terms of rectilinear elements, in the final designs they are replaced by the typical curved shapes in a descriptive procedural fashion.

McCormack and Cagan developed work on branding of automobiles, namely a shape grammar for generating the front-end view of a Buick (McCormack et al., 2004). In this two-dimensional shape grammar, curved lines are used extensively. The curved lines are controlled by parametrically positioned control points. Although it is not explicit, these curves seem to be Bézier curves. A similar strategy will be used in the definition of the profile curve of the base shape of the tableware elements.

Around the same time a shape grammar is developed that features curved shapes, using both straight lines and circular arcs to generate the bottles of Coca-Cola and Head & Shoulders (Chau et al., 2004). Despite mentioning research towards the generalization for NURBS curves, it is not present in this research.

This issue was addressed by Jowers and Earl (2011), who have developed and implemented a curved shape grammar for generating Celtic knots, using quadratic Bézier curves. Their research focuses mainly on the problem of shape recognition and emergence, which is a typical research problem when implementing a shape grammar into a computer program.

Although an implementation was developed in this exercise in order to test formal aspects of the shape grammar rules, it is not the grammar itself that has been implemented, but rather parametric models that correspond to specific derivations of the grammar. Different derivations can be generated, but it is the user who must directly manipulate the rules, selecting the ones to be applied. Therefore, issues like shape recognition and emergence, which are typical of shape grammar implementation, will not be addressed for now.

So, although some work has been developed on shape grammars of curved shapes, these shapes are mostly linear. Research on shape grammars applied to surfaces is still sparse. We hope that this research can contribute to fill in this shortcoming.

DEVELOPMENT OF THE SHAPE GRAMMAR

One of the objectives of this research is to develop a shape grammar that is able to encode the styles, regarding both shape and decoration, of different collections of tableware sets. However, for this first exercise, the goal was set to develop a shape grammar that would encapsulate the style of one collection (Figure 1). The shape grammar should automatically generate the different elements of the selected collection, taking into account that it would be subsequently extended to other collections.

Element types

Even before focusing on any specific collection, a reflection was made on the different types of tableware elements. A first observation on the dimensions of these elements led to establishing a distinction between deep and shallow types. The shallow type category includes the charger plate, the dinner plate and the soup plate, while the deep type cat-

Figure 1
Shape grammar corpus.

egory includes the bowl, the mug and the cup.

Types in the same category were considered formally similar among each other, differing only in terms of dimensions. In the deep type category, if we disregard the handle in the mug and the cup, these types are formally similar to the bowl.

Different types are thus characterized by different sizes, measured both in height and radius. Table 1 illustrates the dimensional relations between the six chosen types within the selected collection, as well as the mentioned distinction between deep and shallow types: in shallow types, radius is larger than height, and so the ratio between these dimensions is higher than 1, whereas in deep types, it is lower than 1.

The shape similarity among types within the same category is interpreted as a parametric variation of the same entity, justifying the development of a parametric shape grammar.

Functional parts

This first observation has also brought attention to the distinction between functional parts within tableware elements. Let's take the example of the soup plate. Three functions can be identified in its shape: the broad border is used to *hold* the plate; the soup needs to be *contained*, and so the dish must have a deeper part for this purpose; and finally, it needs a broad and flat bottom, so it *lays* steady on the table. So the three functions are: holding, containing and laying on the table.

The functional parts were analyzed in terms of dimensions, namely height and radius. The relations between dimensions of the different functional parts are described by a functional configuration. The functional configuration for the soup plate, systematizing the example given above, is shown in Table 2.

Different types feature different functional configurations. For example, to be able to contain liquids, the soup plate and the deep types feature a taller containing part than the dinner plate.

Generally, all three functions are present in each type. However, in some types they are assigned to parts other than the main body of the tableware element. For example, in the mug or the cup, the hold-

Table 1
Classification and dimensions of the different types in one collection

Type	**Charger**	**Dinner**	**Soup**	**Bowl**	**Mug**	**Cup**
Radius (cm)	15,50	13,50	11,50	7,00	4,50	3,75
Height (cm)	3,00	2,50	4,00	8,50	10,00	5,00
Radius/Height	5,16	5,40	2,88	0,82	0,45	0,75
Category	**Shallow types (plates)**			**Deep types**		

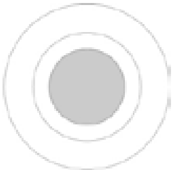
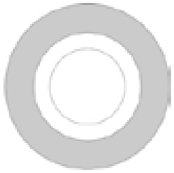
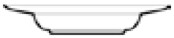
Function	to lay on (ps*)		to contain (ct*)		to hold (pg*)	
radius		46%		20%		35%
height		14%		58%		29%

Table 2
Functional configuration of the soup plate (from the portuguese "pousar", "conter" e "pegar", respectively).*

ing function is assigned to the handle. In its current state, this shape grammar is only encoding shape for the main body of the elements. Parts like the handles in the cups and mugs will be addressed in the future.

Further development of the shape grammar will focus its extension to other collections. It is expected that for the same types within other collections, functional configurations, despite featuring some dimensional variation, are somewhat similar, and therefore characteristic of the type. Variations on this configuration are to be registered as other collections are analyzed, and will be properly integrated into the design system.

Initial shape and first derivation steps

This first analysis is incorporated into the first two rules of the shape grammar, which are applied in the beginning of each derivation of a tableware element (Figure 2).

Derivation begins with the initial shape, which is a referential determining the center of the tableware element, as well as the upward direction (h, from *height*) and the outward direction (w, from *width*). The general dimensions of the tableware element are introduced as input parameters of rule 1, which creates an object in which the element is inscribed. This object is called the *envelope* (Figure 3, en). In the two-dimensional view of the profile, the envelope is represented by a rectangle, or more generally speaking, a quadrilateral - since the rectangle will be subsequently distorted, the general term quadrilateral, or quad, is more appropriate.

The initial envelope is subsequently subdivided into the element's functional parts by rule 2, which is parameterized according to the correspondent functional configuration (Figure 3). Rule 2a subdivides the envelope into three functional parts, and can be applied to the shallow types. For the deep types, rule 2b should be applied, which disregards the holding part (pg).

Derivation of the tableware elements can be split into three phases: initialization - which applies rules 1 and 2 as seen above -, base shape definition

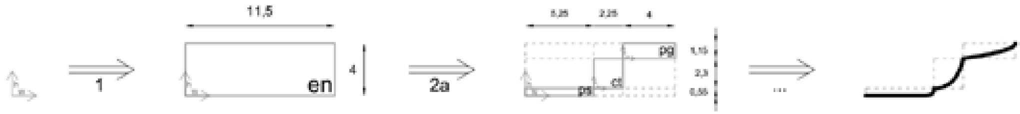


Figure 2
First steps of derivation for the soup plate: envelope creation and functional partitioning.

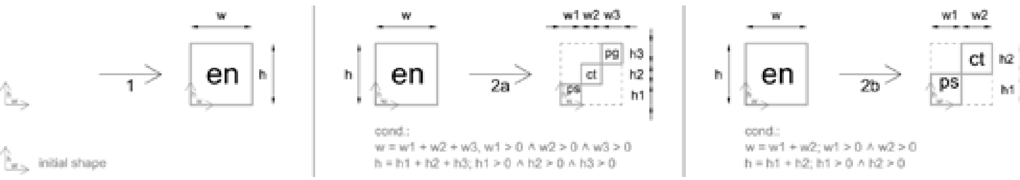


Figure 3
Shape grammar rules for envelope creation and functional partitioning.

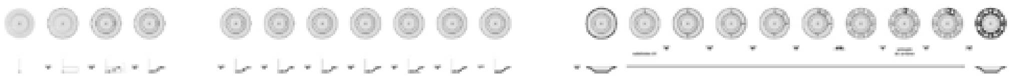


Figure 4
Overview of the soup plate derivation.

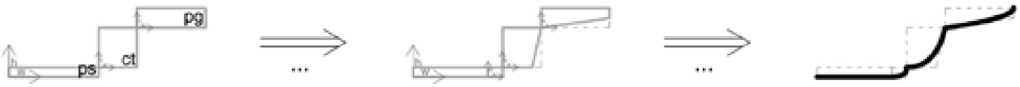


Figure 5
Resumed derivation for base shape of soup plate.

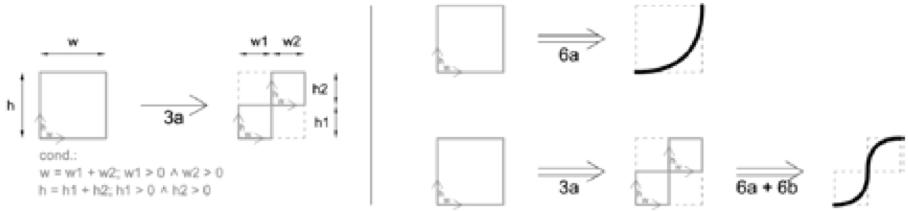


Figure 6
Subdivision rule and example of application: subdivision allows for more complex shapes.

and decoration - which applies subsequent rules (Figure 4). To each phase corresponds a bi-dimensional view, which best illustrates the three-dimensional geometry of tableware elements, as well as the operations applied to them.

Base shape definition

Since the selected collection features circular elements, their base shape can be described as a solid of revolution. Therefore, rules and derivation steps regarding base shape generation are represented by a bi-dimensional profile. For this first approach, the profile thickness is not being considered, and therefore the resulting shape is more accurately described as a surface, rather than as a solid.

The base shape is defined by formal manipulation of the functional parts that result from the initialization phase. In the end, the base shape profile is the product of a combination of quadratic Bézier curves, controlled by their corresponding envelopes (Figure 5). The quadrilateral envelopes are used as auxiliary shapes for defining the Bézier curves inscribed in them.

Therefore, in the base shape definition phase, three types of rules can be applied: subdivision, distortion and substitution.

Subdivision rules in the base shape definition phase (rule 3) are similar to the functional subdivision rules seen previously, the difference being that the resulting envelopes keep the type of the preceding envelope. These rules allow for more complex shapes, through subsequent combination of more than one Bézier curve (Figure 6).

Distortion rules allow to manipulate the quads that correspond to the envelopes, and therefore manipulate the control points of the Bézier curves that will substitute them. Distortion rules can be applied recursively, allowing to generate additional distortions not coded into rules through a compound effect. Figure 7 shows how to obtain this through applying rule 4 recursively and with different transformations - which are shown under the rule application arrow. Parameters are used both for the distortion effect as for the shape matching, and were

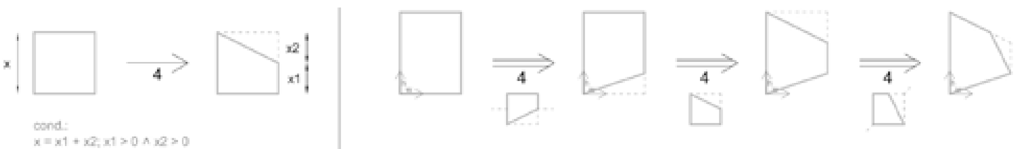


Figure 7
Distortion rule and example of recursive application.

omitted for clarity.

Substitution rules replace the envelopes by their corresponding Bézier curves. For each curve, three of the vertices of the corresponding quad correspond to the curve's control points, whereas the directions of the curve's start and end tangents are defined by the quad's edges (Figure 8).

The rules are allowed to be applied in different order. For example, we can subdivide an already distorted envelope. This is possible because of the parametric nature of the grammar, which allows for perspective transformations (Stiny, 1980). However, the result of applying the rules in a different order is not necessarily the same (Figure 9). In this way, some flexibility is added to the grammar.

Figure 10 shows all the derivation steps for defining the base shape of the soup plate, including the initialization phase. The final step corresponds to the revolution of the profile into a set of surfaces, the actual base shape upon which decoration rules will be subsequently applied.

Decoration

Decoration is achieved through the application of shape grammar rules to the resulting base shape surface set.

Rules for defining the base shape of the tableware element operated on its profile, which is a two-dimensional representation. In the decoration phase, however, and because we are dealing with three-dimensional surfaces, representation of rules and derivations in two dimensions is not straightforward - in fact, neither is imagining them. For this purpose, we make use of the parametric representation of surfaces. In this representation, the Cartesian coordinates of a surface point depend on two different parameters *u* and *v*, allowing for a continuous mapping of a two-dimensional region into space (Pottmann et al., 2007).

A typical example of a parametric representation is a world map. The map's horizontal lines represent coordinates on the surface of the Earth with the same latitude, while the vertical lines correspond to points with the same longitude (Figure 11). Therefore, latitude and longitude can be considered the uv parameters of the Earth's surface. A point with given parameters in the map can be easily and accurately identified using a GPS device. Similarly, lines and shapes can be mapped from the map into the

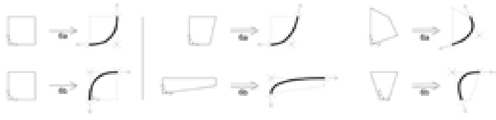


Figure 8
Replacing envelopes for corresponding Bézier curve: substitution rules and examples of its application.

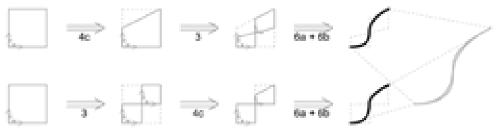


Figure 9
Different sequence order generates different results.

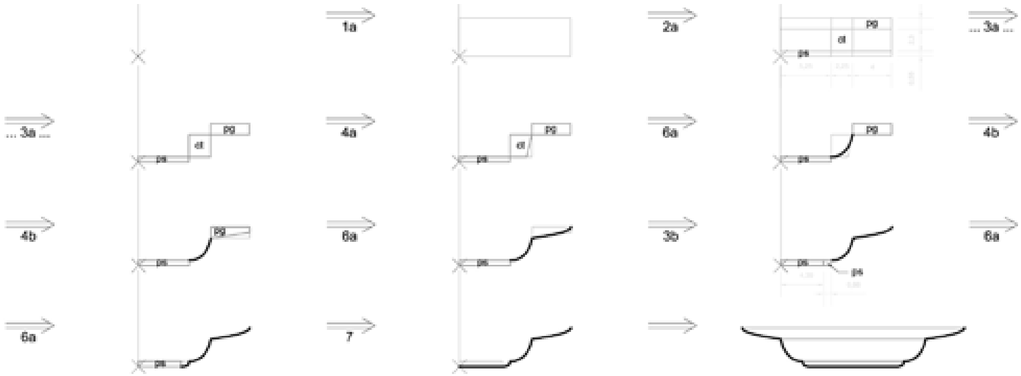


Figure 10
Derivation for base shape of the soup plate.

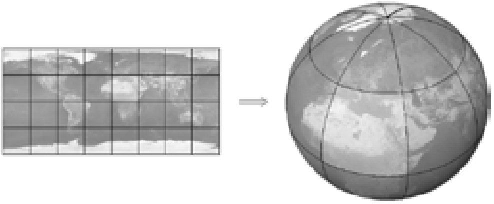


Figure 11
World map as parametric representation of the surface of the Earth (world map from www.free-world-maps.com).

globe and vice-versa.

These mapping operations are used in the decoration phase. In this phase's derivation steps, the tableware elements are represented in two-dimensional space as top views. In the case of the selected collection, these elements correspond to circular objects, and inherently their parts feature circular arcs. In rule description however, such as in the base shape definition rules, surfaces are represented by squares, a generic shape which evokes the two-dimensional nature of the uv parametric representation (Figure 12).

Therefore, rules are mapped into the design in the same way a shape in a map is mapped back and forth into the surface of the Earth. These mapping operations imply the use of non-linear transformations - transformations that map straight lines into curves (Pottmann et al., 2007) - , which are not usually addressed in the shape grammar formalism. In fact, Stiny (1980) states that "a shape rule **a** → **b** applies to a labeled shape **c** when there is a transformation **t** such that **t(a)** is a subshape of **c**" (p. 347), limiting these transformations to translation, rotation, scale and reflection, which he refers to as Euclidean transformations (p. 344). However, the author points out that for transformations other than Euclidean, such as affine or perspective transformations, a parametric grammar should be used (p. 351).

For the development of this grammar, we are assuming that, similarly to affine and perspective transformations, non-linear transformations can be also be used in parametric grammars. This hypothesis should be later proven in order to validate this grammar.

In the selected collection, decoration is based on a) subdivision of surfaces, and b) application of a relief- and contour-based motif onto the resulting subsurfaces (Figure 13).

Subdivision rules are similar to the subdivision operations mentioned previously, except they op-

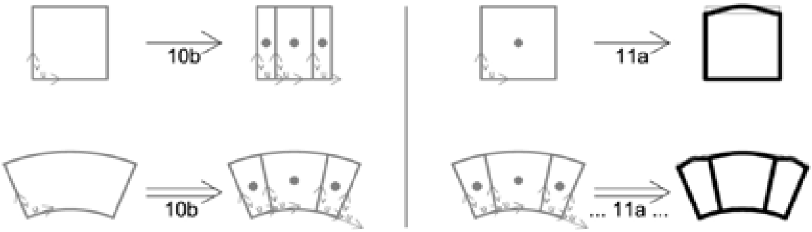


Figure 12
Example of UV mapping: rules are mapped onto surfaces.

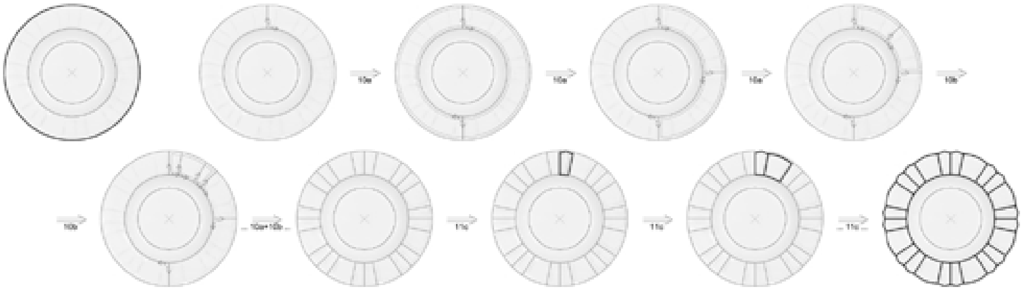


Figure 13
Derivation for decoration of soup plate.

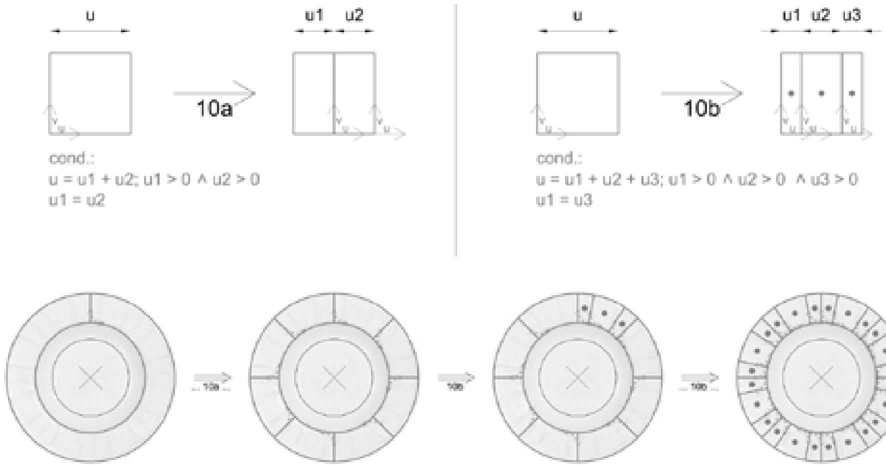


Figure 14
Decoration subdivision rules and application in the soup plate derivation.

erate on the surface's parametric, or UV, space. Rule 10a subdivides the surface into two parts with the same U parameter differential (Figure 14). In the derivation for the selected collection, rule 10a is used recursively to subdivide the plate into eight parametrically equal parts.

Rule 10b subdivides it into three parts, also along U, but in this case the first and third part have the same U parameter differential, which is different for the second independent part. The parametric relations among the parts are variable. In the selected collection, the second part is larger (Figure 14). However, in the corresponding rule this constraint is not set, so to allow for a wider range of variation.

Rule 10b uses a label to mark the subsurfaces to which subsequent decoration rules can be applied. Since the use of labels is still under development and lacking consistency, it has not been addressed in this paper.

Similarly to the base shape definition phase, surfaces resulting from the subdivision operations are to be replaced by more elaborate ones featuring relief-based motifs. For the selected collection, two rules are defined, 11a and 11b, which are to be applied exclusively onto shallow and deep types respectively. Both rules apply a slight depression to the target labelled subsurface, a motif which is typical for the selected collection. However, contrary to rule 11b, rule 11a also changes the subsurface's contour (Figure 15).

Recursive application of motif replacement rules to all labelled subsurfaces is the final stage of the derivation, resulting in a design that belongs to the collection's language (Figure 15).

APPLICATIONS OF THE SHAPE GRAMMAR

Parametric modelling

A three-dimensional parametric grammar is difficult to test without some kind of implementation. On the one hand, the combination of several parameters corresponds to a large number of solutions.

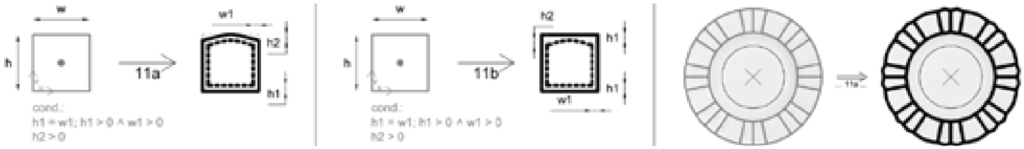
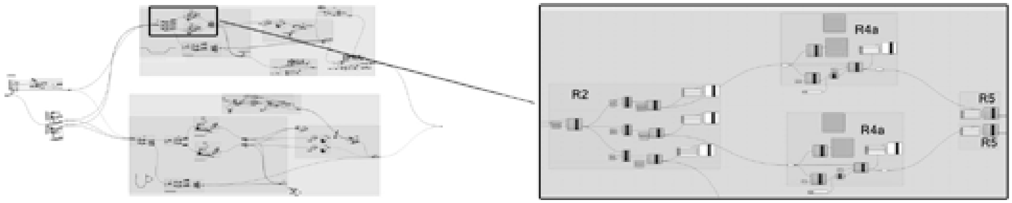


Figure 15
Motif replacement rules and application in the soup plate derivation.

Figure 16
Parametric model developed in Grasshopper: using rules as groups of components.



On the other hand, some three-dimensional geometric operations are difficult to represent in two-dimensional drawing, such as the surface mapping operations.

Therefore a computational model was developed in Grasshopper, a visual programming interface that interacts with geometrical modelling software Rhinoceros, and allows implementing, and therefore evaluating, parametric models. It should be noted that the Grasshopper model is not considered an implementation of the shape grammar. However, if we consider that the result of the derivation of a parametric shape grammar is a parametric model, than we can argue that we are implementing a derivation. Actually, the Grasshopper model was developed so that rules can be identified as groups of components, in a modular fashion (Figure 16).

With this tool, two derivations of the soup plate were implemented as parametric models. The two derivations differ slightly, having different rules applied in the base shape. Then, for each derivation, two models were generated using different parameter configurations. Therefore, a total of four digital models were generated in Grasshopper (Table 3). These models were to be later produced through rapid prototyping.

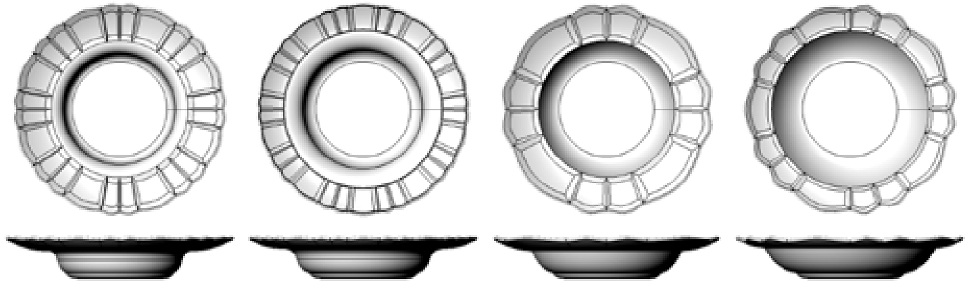
3D printing

The digital models generated in the Grasshopper program were materialized through available 3D Printing technology. For saving purposes, four quarters of dishes were produced, instead of four complete dishes (Figure 17). This was also useful to evaluate the results in terms of their section.

Prototyping the models provided for a general first impression about the models being generated, namely in terms of scale and weight. The 3D printed models are especially useful for communication purposes, allowing to better illustrate the project design, either to faculty members as well as to potential partners in the industry.

Further research will aim at determining if these

Table 3
Digital models of derivations of the shape grammar.



Derivation 1 Parameters 1A	Derivation 1 Parameters 1B	Derivation 2 Parameters 2A	Derivation 2 Parameters 2B

3D printed models are suitable for mold making, and if it is possible to use 3D printing for digital fabrication, i.e., for producing final products.

CONCLUSIONS

This exercise brought the attention to the many questions that should be answered in order for the mass customization paradigm to be applied to ceramic tableware. Focusing particularly on the development of the shape grammar, the manipulation of three-dimensional and predominantly curved shapes poses as the main challenge, which needs to be mastered in order to serve as an effective design system.

However, the success of this first mockup poses as a good indicator for further research, which is planned to develop along the three systems.

Future developments

Some aspects of the Shape Grammar formalism are to be further addressed, stabilizing the design system so it can be extended to other collections and element types, namely the validation of mapping operations, as well as control mechanisms such as labels and parameter intervals. Concerning implementation, although Grasshopper was used in this first mockup, a study must be conducted on the available programming technologies for implementing the design system. Concerning the production system, a thorough research on production techniques is to be developed, both for handcrafted and industrial ceramics manufacturing. Last but not least, establishing a partnership with a manufacturer is a key factor for the success of this research.

ACKNOWLEDGEMENTS

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Figure 17
3D printed prototypes.

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Grandstand Grammar and its Computer Implementation

A computational approach to facilitate decision making and encourage efficiency in the design of sports facilities

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Abstract. *In sports facilities, a grandstand is the structure which provides good sight quality and safety evacuation conditions for the spectators. Grandstand plays important functional and formative roles in sports facilities, and especially in large scale stadia. This paper argues the notion of shape grammar and its computer implementation will solve the difficulties in grandstand design. The authors identify the specific difficulties of grandstand design, then set the aims of the grammatical computer tool. Afterwards the shape grammar of grandstand design is formulated, and a computer tool is developed based on the grammar. At last, the paper discusses the application and usage of the grammar and the computer tool both in early design phase and design development phase with a design practice case study of a large scale stadium.*
Keywords. *Grandstand design; shape grammar; parametric modelling.*

INTRODUCTION

In sports facilities, a grandstand is the structure which provides good sight quality and safety evacuation conditions for the spectators. Grandstand plays important functional and formative roles in sports facilities, and especially in large scale stadia. Apart from the function and form of the grandstand, the designs of other parts of stadium such as the facade surface and the roof are closely related to the grandstand, and most of the interior rooms are placed under the grandstand. In the very early design phase of a large scale stadium, the design of the grandstand must be considered to accommodate the spectators and the other basic need of the building. Traditionally, the process of a grandstand design trends to be complicated and tedious. Therefore the in the early phase of the design practice, architects are likely to use existing grandstand design with similar condition rather than design a new grandstand for the project. In the design development phase, modification of grandstand design will result in the large amount of remaking of documentation. Furthermore, the modification process of the other parts of the building would be delayed by the grandstand. Three problems are identified in the traditional grand stand approach. How to provide a highly customized grandstand model in early design phase? How to provide rapid response to the modifications in the design developments phase? How to rapidly negotiate the relationship between grandstand and the other parts of the building?

This paper argues the notion of shape grammar and its computer implementation will give a solution to the above three problems. Similar studies show the parametric design approaches to facilitate the grandstand design (Hudson, 2010; Miller, 2009). However, the studies trend to focus on the grandstand as an isolated part. The relationship between the grandstand and the other parts of the stadium is not explored. The design rules of grandstand is are not presented in formal ways. Grandstand design follows strict and complicated function rules and patterns. The shape grammar approach provides a computational and logic device for recording design rules and patterns. Computer tools can be made base on a shape grammar to solve specific design problems.

In the following part, the authors identify the specific difficulties of grandstand design, then set the aims of the grammatical computer tool. Afterwards the shape grammar of grandstand design is formulated, and a computer tool is developed based on the grammar. At last, the paper discusses the application and usage of the grammar and the computer tool both in early design phase and design development phase with a design practice case study of a large scale stadium.

THE DIFFICULTIES IN GRANDSTAND DESIGN AND THE AIMS OF THE GRAMMATICAL COMPUTER TOOL

The difficulties in grandstand design

The design of grandstand requires complicated professional knowledge. The difficulties in grandstand design can be identified in the following aspects:

1. Section design. The raise of each row should be precisely calculated to guarantee the sight quality of the spectators. The amount of raise will be affected by the type of game, the first row profile, the elevation of the first row, C value and the row distance. The calculation could be time consuming and tedious if was done manually.
2. Plan drawing. After the configuration of the first row profile, the plan drawing is a tedious process. The designer spend most of the time drafting the offset row profiles. If the first row profile is modified, the whole drawing will have to be remade.
3. The capacity calculation in the early design phase. The capacity is related to multiple factors such as the area of the grandstand, the number of aisles, the number of vomitories, row distance and the seat width. The precise capacity can only be obtained at the very late phase of grandstand design. If the row profiles is a curve, the distribution of seats will be a lot more difficult than the linear row profile.
4. The generation of the 3D profile of the grandstand boundary. For the case that the boundary is not parallel with the row profile, the profile of the boundary will be a 3D curve and define the skyline of the grandstand. It plays an important role in the façade of the building and acts as a key reference of the roof. The curve can only be generated in the late phase of grandstand design.

The aims of the grammatical grandstand design tool

The digital model should be served a reusable tools to assist the designs of varied grandstands for different projects. After the identification of the difficulties in grandstand design, the tool should achieve the following aims:

1. Ease for use. In this case the ease for use contains two aspects: the easy acquisition of design knowledge and the friendly user interface. The designers who are not familiar with grandstand design could quickly gain the according knowledge in a systematic way. The user-friendly interface could promote the designers to use the tool and focus on the grandstand design regardless of their knowledge of computer programming and 3D modeling.
2. Real-time visual feedback. The 3D model can be updated synchronously with the design conditions and parameters.

3. Real-time performance feedback. The performance indicators such as capacity, elevation of each level and the sight quality of each seat can be updated with the 3D model.
4. Enhance design efficiency. Majority of the manual works can be overtaken by the computer tool.
5. Enhance design quality. More energy could be put in the generation of alternatives, exploring of design space, refinement of design decision making. The 3D model would help reduce design mistakes that are difficult to be reflected in 2D drawings.

THE FORMULATION OF THE GRANDSTAND GRAMMAR

Subdivision of tasks

Considering the complicity of the grandstand design, the design task is divided into the following sub tasks:

1. Generation of the plans of rows. The task contains the generation of the plan profile of each row, the position of the vomitory, seat distribution guide line and the estimated capacity of the grandstand. The input shapes are the first row profile, boundary of the grandstand, focus point and the aisle axis. The input parameters are row distance, number of rows, aisle width, evacuation method, vomitory width, vomitory start level, vomitory end level, seat width and seat offset. The outputs are the plan shapes of rows, seat guide lines and estimated capacity.
2. Aisle generation. The input shapes are the first row profile and the focus point. Input parameters are seat width, maxim seat number in a row, row distance, number of rows and aisle width. The outputs are the aisle axis and aisle region curve. The generation could be controlled automatically or manually. In the automatic generation, the distance between the aisles is determined by the maxim number of seats and the seat width. Since the position of aisle is influenced by other factors such as the space beneath the grandstand and the position of columns and beams, the user can also manually input the aisle axis. The position of vomitory will change according to the aisle axis.
3. Raise calculation. The raise of each row away from its low row is calculated in the task. The input shape are the first row profile and the focus point. The input parameters are number of rows, row distance and C value. Calculation is made according to equation (1). In the equation, Y is the elevation from the focus point to eye point, K is the number of rows, C is C value (John and Sheard, 2000). The output are the elevation of each row and the sightlines.

$$Yn = [(Yn\text{-}1 + (Kn\text{-}1) \times C] \times Xn / (Xn\text{-}1) \qquad (1)$$

4. Generation of the grandstand 3D model. The task elevates the shapes on the construction plane to their designed height. Then the solid model are generated from the shapes. For the consideration of quick feedback and the time saving from the solid computation, the user can choose only to elevate the curves rather than generate the solid models. The input shapes are all the row profiles and seat guide lines. The input parameters are the elevations of the shapes. The output are the elevated shapes and solids.
5. Seat distribution. The task inserts seats on the seat guide lines and calculate the precise capacity of the grandstand. The input shapes are the seat guide lines, seat rectangle and the 3D seat model. The input parameters are the dimensions of the seat. The output are the inserted seat shapes and the precise capacity.
6. Sight quality analysis. The task analyses the sight quality of each seat. The inputs are the seats model, 3D model of possible obstructive, seated people model and eye level height. The outputs are the sight quality indicators such as view angle and view distance. Collision test between the sight line and the possible obstructive will be operated to show the blocked sight lines. First person perspective render can also be obtained to simulate the view of spectators.

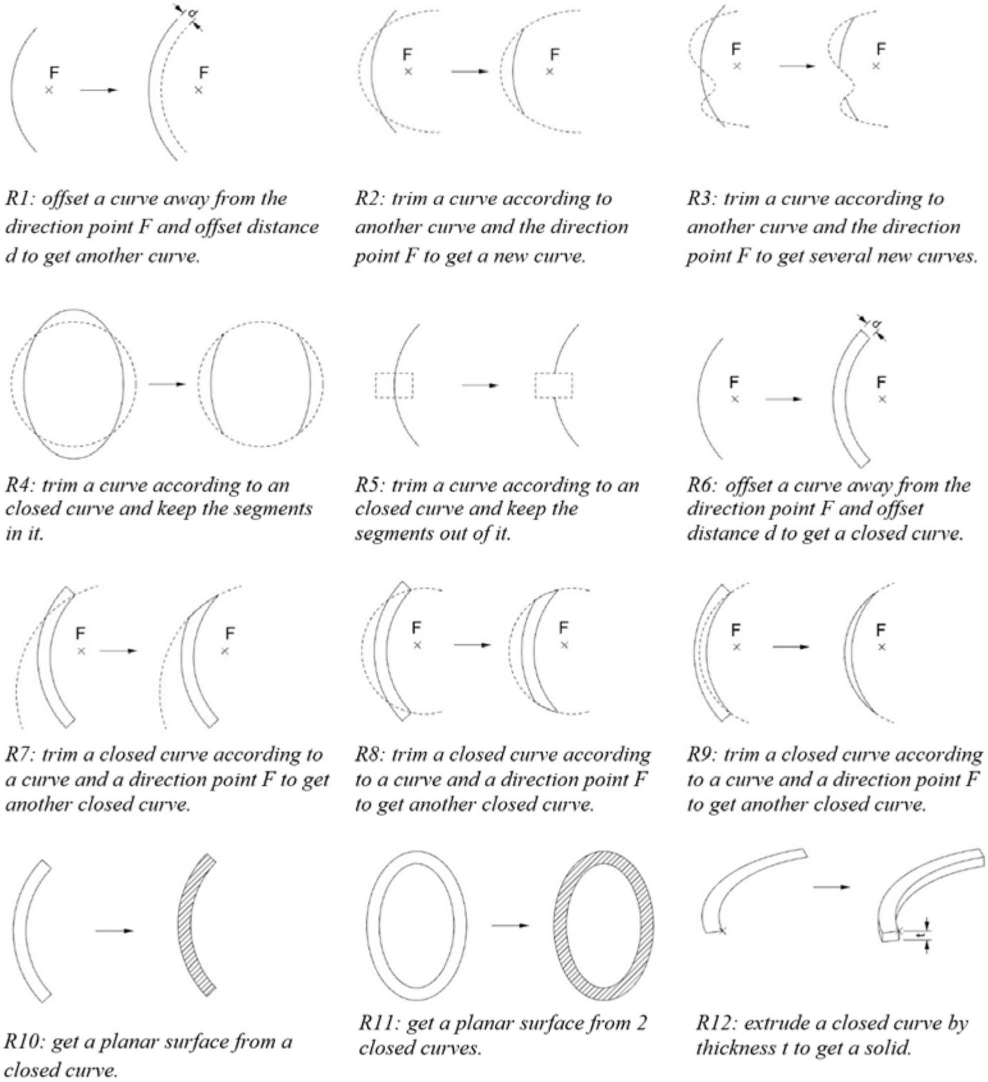


Figure 1
R1 to R12 are the rules of row and seat guide curve generation.

The contents of Grandstand Grammar

After the identification of the design tasks, the rules can be translated to a shape grammar called Grandstand Grammar (GG). Rules in GG are organized into 4 groups: rules of row and seat guide curve generation (Figure 1); rules of aisle generation (Figure 2); rules of seat distribution (Figure 3); rules of elevation calculation and elements translation (Figure 4). Figures 5 to 7 show the process of using GG to generate a single tier grandstand.

Figure 2
R13 and R14 are the rules of aisle generation.

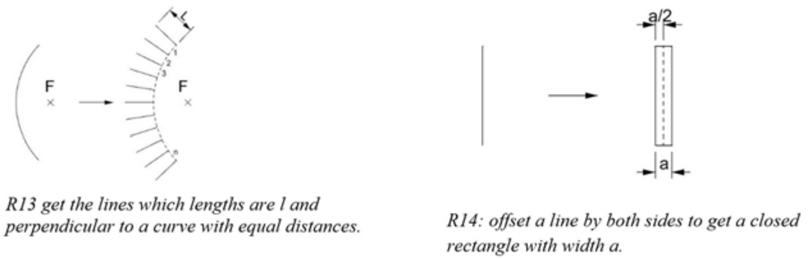


Figure 3
R15 to R19 are the rules of seat distribution.

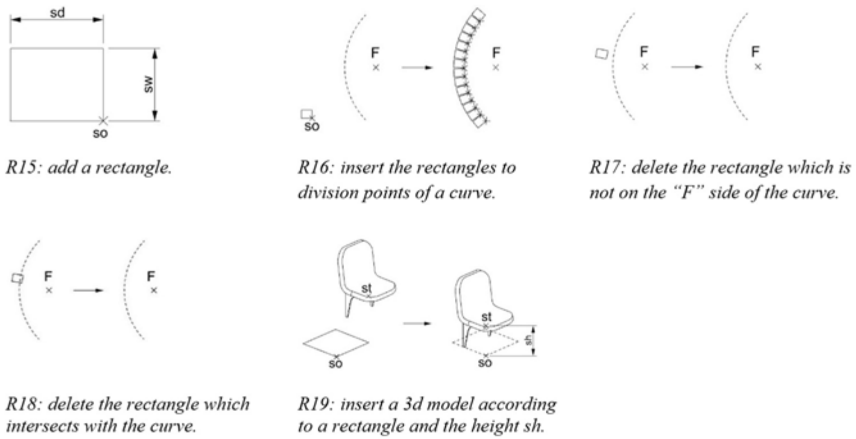
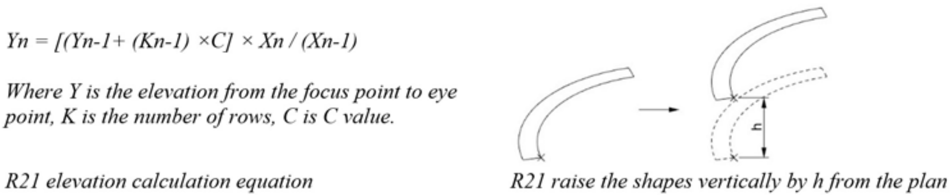


Figure 4
R20 and R21 are the rules of elevation calculation and elements translation.



THE COMPUTER IMPLEMENTATION OF GG

The goal of the computer implementation of GG is to develop a reusable tool for grandstand design. The stability and ease for use should be considered. The user could design with the tool without refering to the detail rules. Therefore the rules should be sealed in the tool and not to be exposed to the users in order to avoid the miss-operation and the confusion of the user. The input and output of the tool should reflect the simple need of the grandstand design. Grasshopper in Rhino3D is chosen as the parametric modeling platform. Scince the seat distritution task is strongly relied on the plan drawing task, the 2 tasks are incoporated into 1 component. The components of aisle axis generation, elevation calculation and 3D model generation are also developed (Figure 8). İnitial sets of parameters are introdued to the components to guarentee the ease of use. The user can use and connect the components to solve design problems of the grandstand.

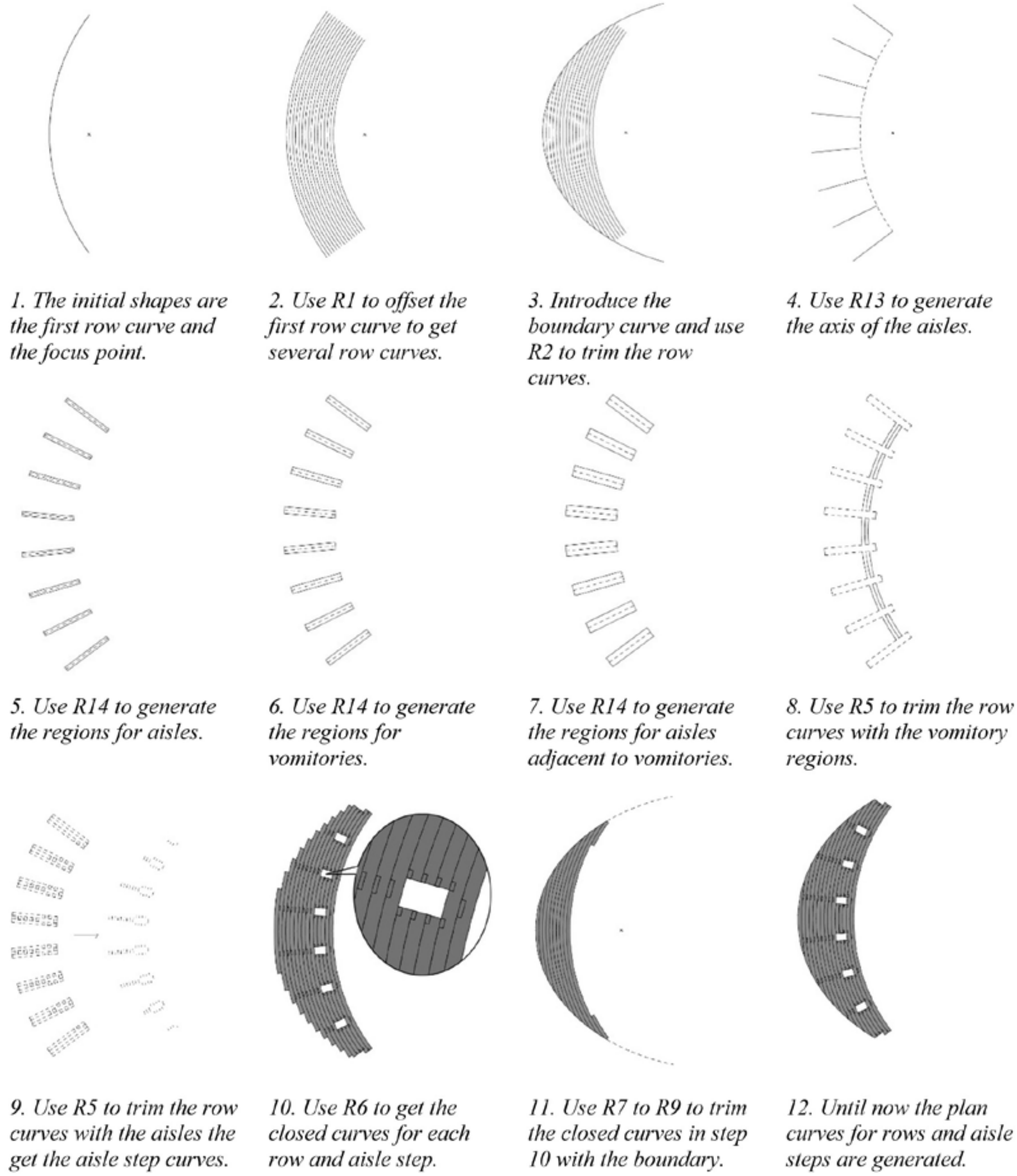


Figure 5
Step 1 to 9 show the generation of the plan curves for rows and aisle steps.

Figure 6
Step 13 to 16 show the population of seats.

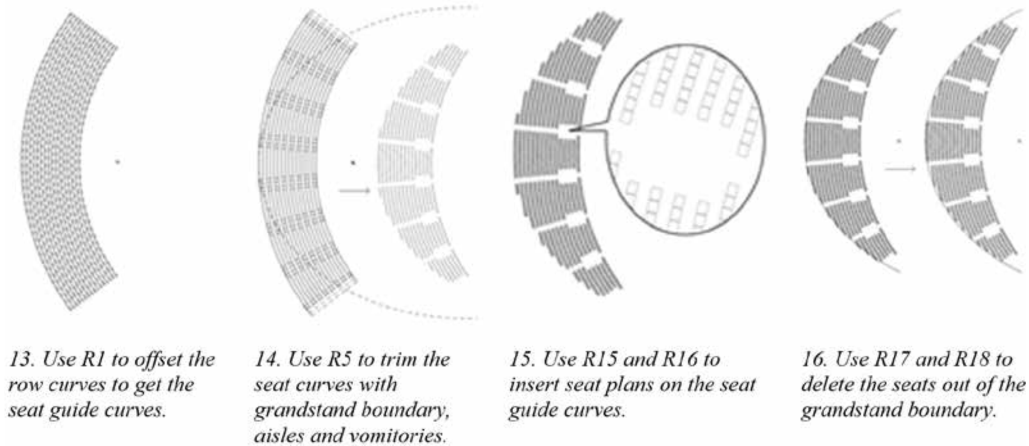


Figure 7
Step 17 to 19 show the generation of the whole grandstand 3d model.

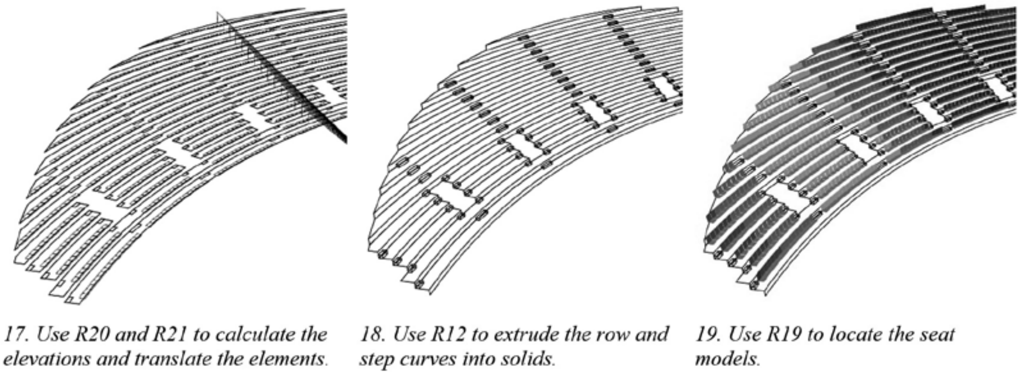
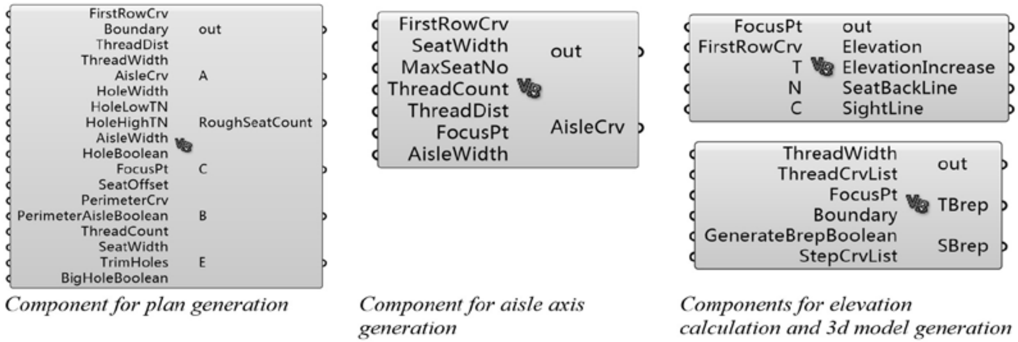


Figure 8
Main components of the grandstand design tool.



THE APPLICATION OF GG AND ITS COMPUTER TOOL

GG and its computer tool is applied to the design practice of a stadium with 25000 seats. In the preparation phase of the project, new designers were trained to learn the knowledge of grandstand design and the use of the parametric model. Their abilities to build the 3D grandstand model varied greatly in terms of the understanding of the grandstand rules and the 3D modeling software. However, the learning curves were benefited from the systematically formulated shape grammar, friendly user interface and the detailed initial set of parameters. All of the designers could basically operate the tool in the 4 hours session of training. After the training they could use the tool to generate simple grandstand 3D models. As we should point out, the tool did not turn them into experts of grandstand design in the very short time span. Also the digital tool should not be seen as a guarantee of good grandstand design. In the design process, the model should always be reviewed and evaluated by the experts to avoid design mistakes.

In the design competition phase, the tool was used to guide the design decision making. A main issue of the project is the configuration of seat number on the tiers of the two sides. The change of configuration has an important impact on the height of the grandstand: symmetry configuration results in the same height of both sides; uneven configuration results in different height of sides. Multiple designs were generated to reflect the relationship between the height and the seat configuration.

In Grasshopper, model of the grandstand and the other parts are inter-related to each other. The first row profile and the boundary of the grandstand are the key shapes for both grandstand design and roof design. Therefore different design tasks could share some key parameters. The design of the 2 parts can be carried out simultaneously and separately because of the parametric feature of the model. Designers could parametrically model the roof according to its relationship with the grandstand. Therefore the roof model can be updated in the grandstand process. The designer could also adjust the grandstand design according to the evaluation of the roof. The relationship between the grandstand and the whole building was reflected in realtime to enhance the design communication and facilitate the making of design decision (Figure 9).

İn the design develpment phase, the parametric model was used to tackle the intense design modifications. During the process, several modifications were carried out. Curvature and elevatioin of the first row profile, row distance, seat width, number of rows, elevation of the upper tier, distance between aisles, position of vomitories and the boudary of the upper east tier are changed compare to the grandstand in the design competion phase. Thanks to the rapid response and the flexibility of the parametric model, the grandstand designs were quickly updated to facilitate the modifications of the other parts of the building (Figure 10).

During the design practice, the aims of GG and its computer implementation were verified. The combination of shape grammar and parametric modeling enhance the learning experience of the grandstand design knowledge. Real-time 3D visual feedback, performance feedback and the integration of the whole building enables the architect to widely explore the design space in the early design phase. İn the design develpment phase, the parmetric model could cope with the multiple design modifications and promote the efficiency of the whole building.

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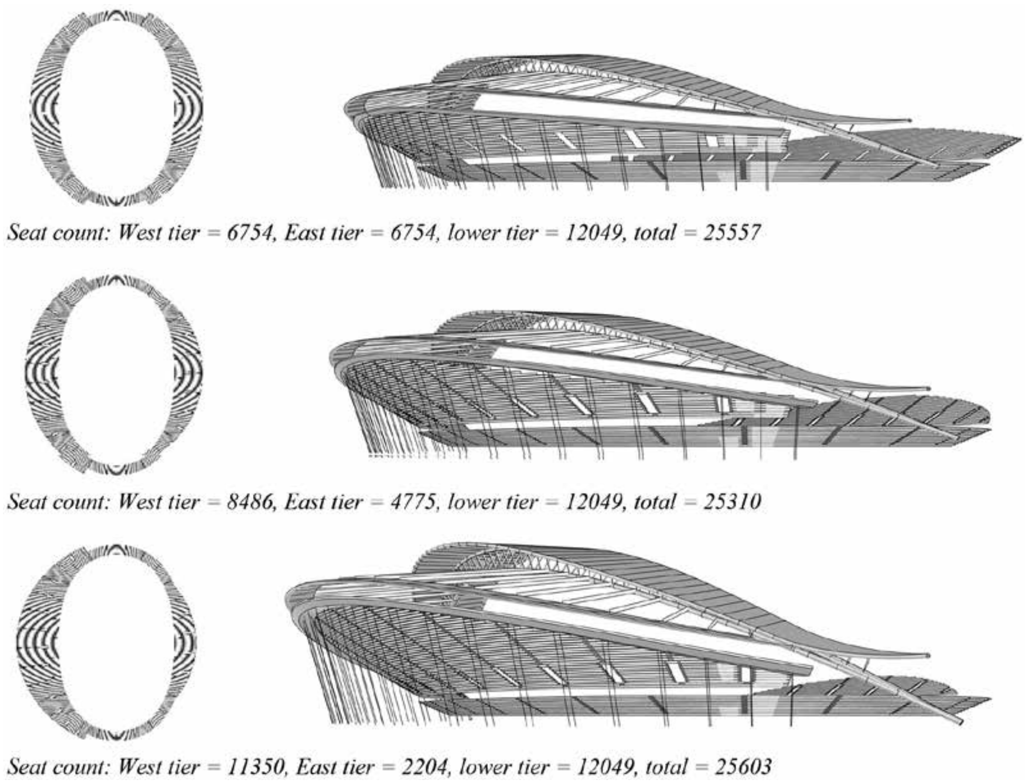

Figure 9
3 grandstand designs with approximate 25000 seats. Different seat population of the west and east tiers result in different heights and form of the grandstands and the associated roof structures.

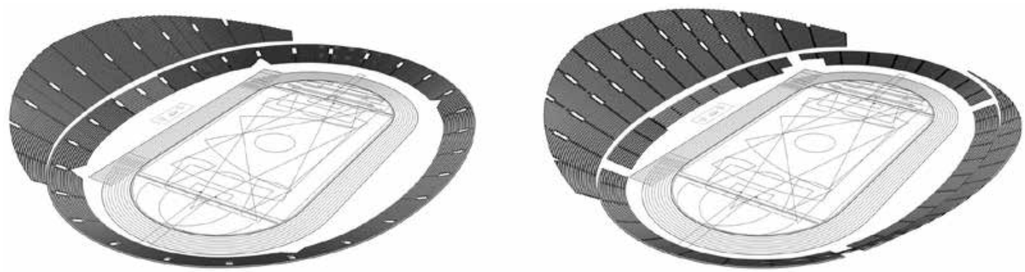

Figure 10
grandstand design of the schematic design phase (left) and the design development phase (right). Many parameters were changed during the design process. The model can be updated quickly according to the adjustment of the parameters.

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From Point Cloud to Shape Grammar to Grammatical Transformations

Using Terrestrial Laser surveying to develop and compare shape grammars

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Abstract. *This paper describes a generative design approach integrating real building data in the process of developing a shape grammar. The goal is to assess to which extent it is feasible the use of a reverse engineering procedure to acquire actual building data and what kind of impact it may have on the development of a shape grammar.*
The paper describes the use of Terrestrial Laser Scanning (TLS) techniques to acquire information on the São Vicente de Fora church, then the use of such information to develop the corresponding shape grammar, and finally the comparison of this grammar with the grammar of Alberti's treatise, to determine the grammatical transformations that occurred between the two grammars.
Keywords. *Alberti, shape grammar, shape recognition, design automation, transformation in design.*

INTRODUCTION

This paper is centered on the construction of the shape grammar of a Portuguese church called São Vicente de Fora. For this propose a point cloud from a TLS surveying was used and a part of a church element (a Doric base) was then closely analyzed.

This research is part of a wider project aimed at decoding Alberti's treatise De Re Aedificatoria by inferring the corresponding shape grammar using the computational framework provided by description grammars (Stiny, 1981) and shape grammars (Stiny and Gips, 1972). The goal is to compare the grammar of the treatise with the grammar of actual buildings to determine the extension of Alberti's influence on Portuguese architecture in the counter-reform period (Kruger et al., 2011) to determine the grammatical transformations (Knight, 1983) that occurred from the original Albertian grammar to the actual buildings grammars.

Established in 1147 by King Afonso Henriques both the monastery and its church of São Vicente de Fora had their reformation by King Filipe I in the 16th century.

It is believed that these renovations followed drawings of Juan de Herrera who was in Lisboa by 1580-1583 and the drawings of Filipe Terzi (Soromenho, 1995). The Portuguese architect Baltazar

Álvares was in charge of directing the construction from 1597 to 1624.

The church has a unique nave, with a transept and a deep main chapel. The walls have pilasters ornamented with a Doric base, a plain shaft and an almost Corinthian Capital with one level of leafs and in the center of the symbols of Saint Vincent and Saint Sebastian. The entablature is Doric with friezes, grooves and mutules. The main nave cradle vault is coffered and its façades have intercommunicating chapels built from 1605 to 1629. There was a dome over the transept that collapsed during the 1755 earthquake.

In the experiment described in this paper, TLS techniques (Mateus, 2012) were used to acquire information from the existing church building and work was focused on the column system. A mesh surface of the church elements was generated from the point cloud obtained using TLS. A Doric column base section line was then detached from that mesh. A process of analysis and evaluation of such line will be showed in the final section of this paper.

METHODOLOGY

There was a previous survey of the building using a phase-based laser scanner (FARO Focus 3D) as shown in Figure 1. The scanner was placed in 24 different stations for the acquisition of colored point clouds. After the registration process a colored point cloud model (PCM) was obtained. The registration and decimation of the point clouds were done with the open source software MeshLAB. For the purpose of this work it was considered a local coordinate frame, aligned with the main directions of the church.

The alignment intended to merge pairs of clouds. The final alignment of the PCM was done using their matrix and was the basis for the extraction of ortho images, multiple sections and triangulated models. Several 2D drawings were produced using JRC software. The final project .Aln containing the alignment of the 24 point clouds was sectioned in a dozen of vertical and horizontal planes configuring the multiple planes, sections and elevations of the church. Some of these drawings were then used as raster images for Autocad and Rhinoceros. Finally, after using the 2D drawings from the laser scanning survey in the construction of the grammar, an element was chosen to evaluate and compare with Alberti's rules for drawing such type of element. Namely, a subset of the point cloud that contained the best column was chosen for the analysis. The information contained in the retrieved data was used to develop the grammar of the column system of São Vicente de Fora. For this purpose we only considered a column and the intercolumn.

This grammar was then compared them with the Column System shape grammar inferred from Albert`s treatise. The deviations were analyzed to identify which rules transformations were needed to obtain the new grammar from the treatise grammar, and then to determine to which extent Alberti's rules are present in the column system of São Vicente de Fora.

SÃO VICENTE DE FORA SHAPE GRAMMAR

In this article we show the rules needed to generate first a colonnade and then the church main nave interior facade by adapting previously developed Doric and Corinthian grammars, which are part of the column system grammar developed after Albert`s treatise.

The Albertian grammar was developed as a parallel grammar encompassing four views: plan, section, elevation, and axonometric (Coutinho et al., 2011). The first three views are developed in the Cartesian product of the algebras U12 and V12, and the fourth of the algebras U13, U33 and V13. The São Vicente de Fora grammar has the same structure. Each grammar rule has a section containing parameters and descriptions and, when needed, a set of functions organized in a way similar to the one used in previous grammars (Duarte et al., 2013). In this article, we show only the elevation view due to space constraints.

Rule 0 has on its left side an empty set and on its right side a guide line extracted from the site

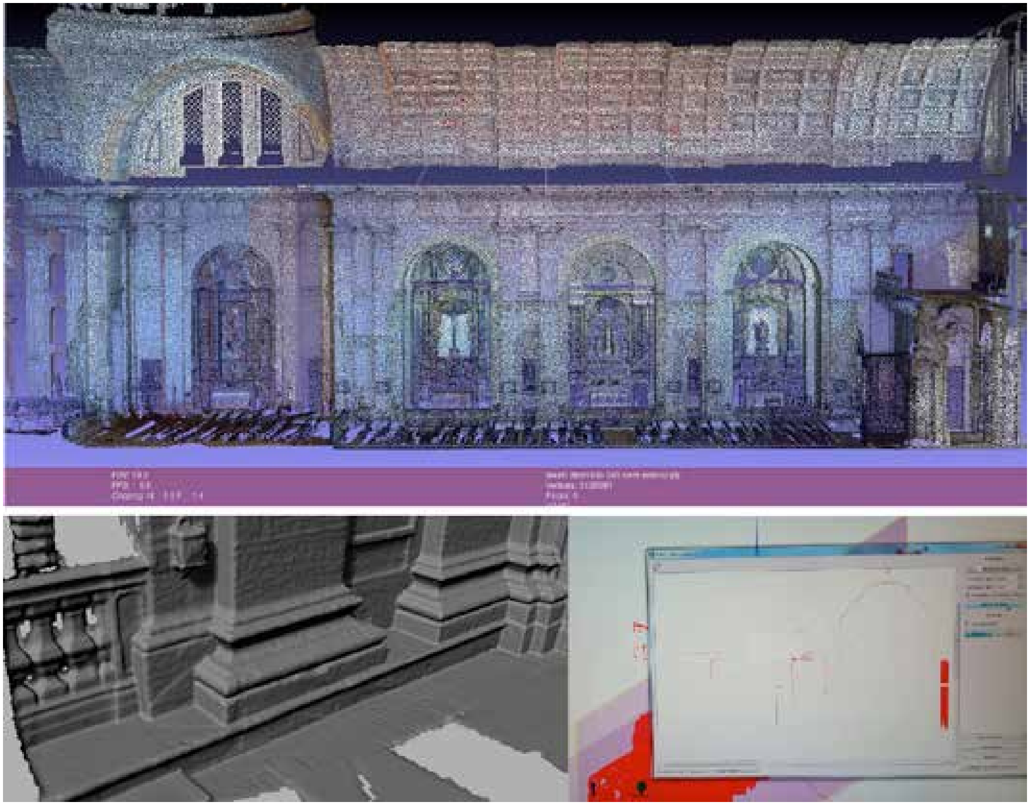


Figure 1
PCM of São Vicente Fora. 2d images from JRC. Column base Mesh surface.

plot, which goes from point A to point A10. Rule 1 generates recursively a generic structure of the church main compositional elements in elevation. This grid contains a set of labels A, B, C and D inserted in a horizontal line from the bottom to the highest central line of the barrel vault ceiling. Each label has several sublabels from Kn to Kn-1 being K ∈ {A} and n>1; n ∈ {1, 2, 3, 4, 5, 6, 7, 8, 9, 10} and K ∈ {B, C, D} and n>1; n ∈ {1, 2, 4, 6, 7, 8, 9, 10}. The lines containing the set points {A, D} and {A3, D3} are mirror axes. The equation of this set is L=wr+4d+2ic+3/2IC+M; where the mirrored part of the main nave is M=4d+2ic+3/2IC+w1; wr is the church high chorus width, d is the pilaster width, ic is the inter chapel's intercolumn, and IC is the main intercolumn. M relates to a quarter of the church's main nave, measured closer to the transept, w1 is the remaining width, which goes from the pilaster axis to the beginning of the arch. Finally L is equal to ½ of the church's main nave plot minus M. In Rule 2 an insertion point (A2) is given to start the generation of a proto pilaster. This point is obtained from the interior of the church structure both in plan and in section using the previous rule. Rule 3 call previously developed grammars to insert detailed base, shaft and capital. Rule 4 inserts an arch from a lateral chapel and a point B. Rule 5 takes the former arch and inserts a Doric entablature with triglyphs and a point C using point B as a reference. Rule 6 inserts the barrel vault ceiling on the top of the entablature

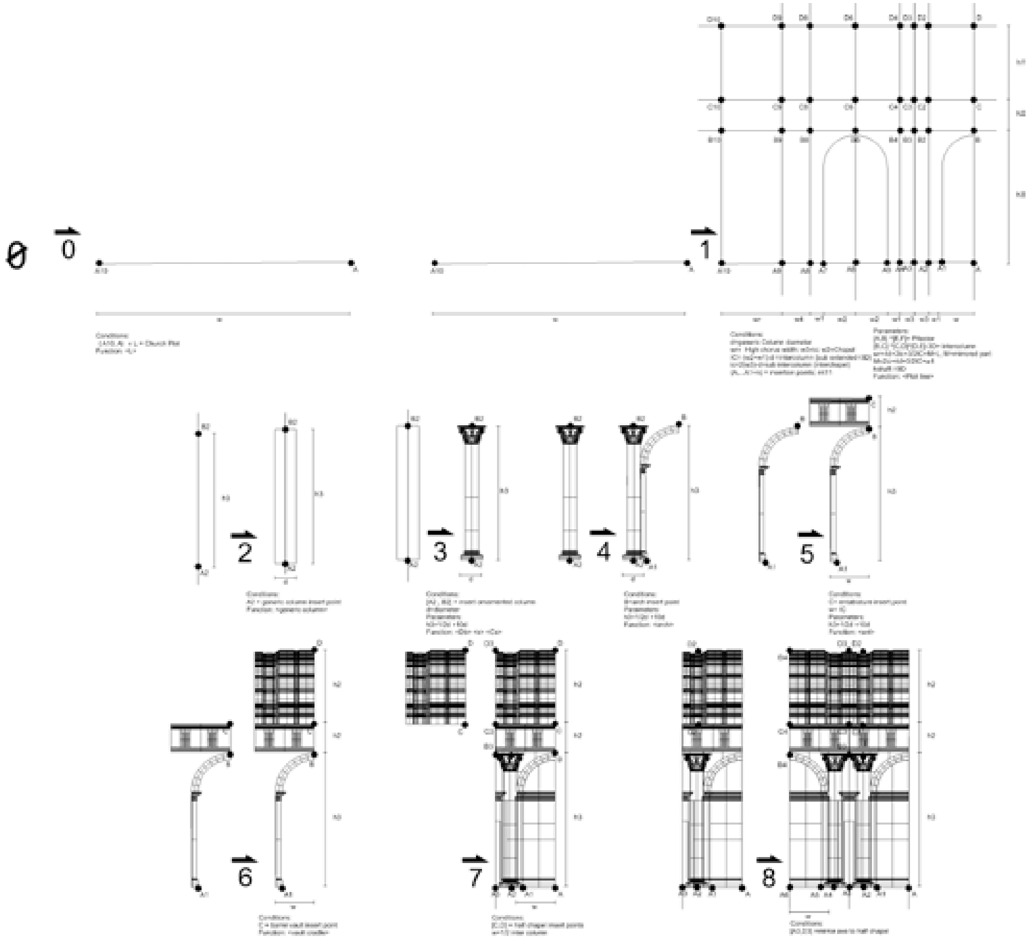


Figure 2
São Vicente de Fora church shape grammar rules.

and a point D using point C as the insertion point. Rule 7 inserts a half chapel and a pilaster and a line with A3 and C3 points. Rule 8 mirrors the half chapel using points A3 and C3 to define the mirror axis. Rule 9 inserts a half chapel, a sub inter column (ic) and an axis from point A6 to D6. Rule 10 mirrors two sets of pilasters (with labels A9, A8, A4, A2) using the axis with points A and D as the mirror line. Rule 11 generates the space to accommodate the high chorus using the pilasters with labels A9, A8, A4, A2 and A1`. Rule 12 (e me ma) erases labels. A 3D model of the main nave was generated by applying the grammar rules. Rules are presented in Figure 2.

NEW SHAPES FROM AN OPTIMIZATION PROTOCOL - THOUGHTS ON EMBEDDING

As mentioned above, the experiment described in this paper relates to the extraction of data from the 3D model generated out of the point cloud model

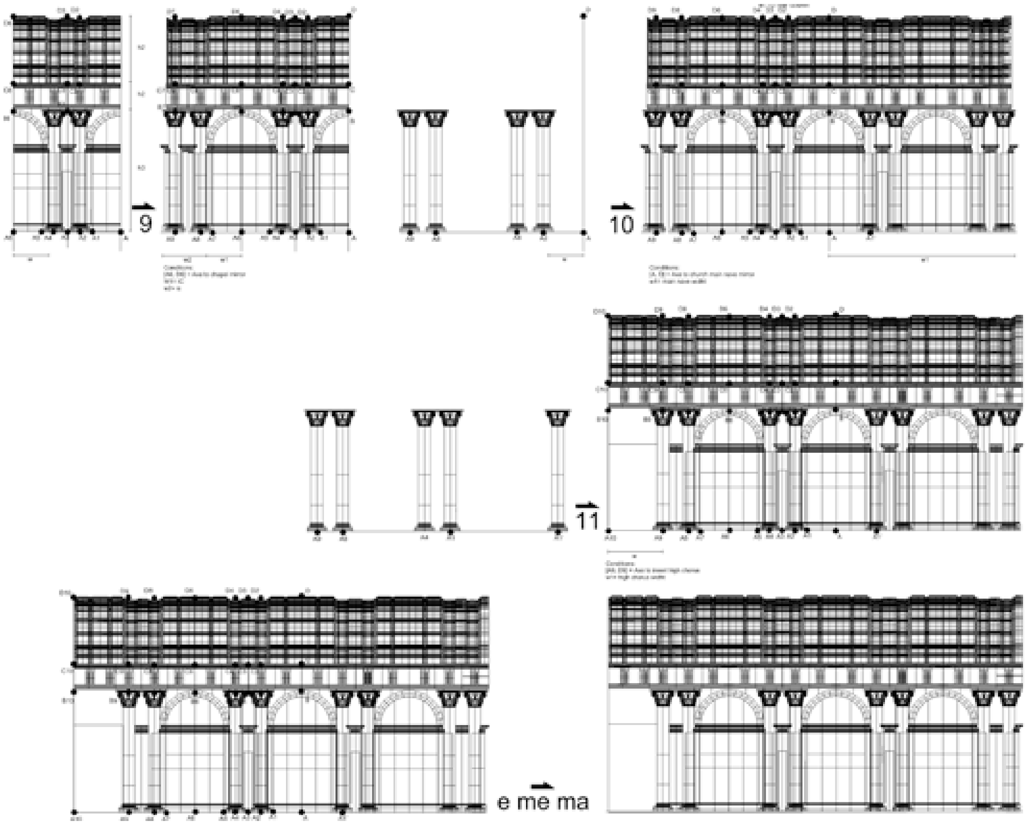


Figure 2 continued
São Vicente de Fora church
shape grammar rules.

and then the analysis of part of it elements.

There are two main concepts that were taken into consideration in the task of evaluating a line extracted from the point cloud. One is the notion of LCS system (Figure 3) mentioned in Alberti's De Re Aedificatoria and the other is George Stiny's notion of embedding.

In Book VII, Chapter VII of the Re Aedificatoria (Alberti, 2011), while describing the Bases and the Capitals of the column system, Alberti mentions that these can be constructed from a minimum vocabulary composed by the letters L, C, S, reversed C and reversed S. Is to be noted that Alberti`s original treatise edition contains no drawings.

The combination of these L, C, S elements and their parametric variation generate the moulds Ovule, Channel, Wave and Gulens. In turn, the combination of these moulds gives different column system elements, such as Pedestal, Base, Column (Shaft), Capital and Entablature. Finally, these might be used to obtain different combinations of Doric, Ionic, Corinthian and Composite style elements. The combinations of these column system elements may produce around 900 different columns. This is the size of the language of columns that can be generated from the LCS system, and which might be recognized using the system showed in the next section. In this way, Alberti was providing a proce-

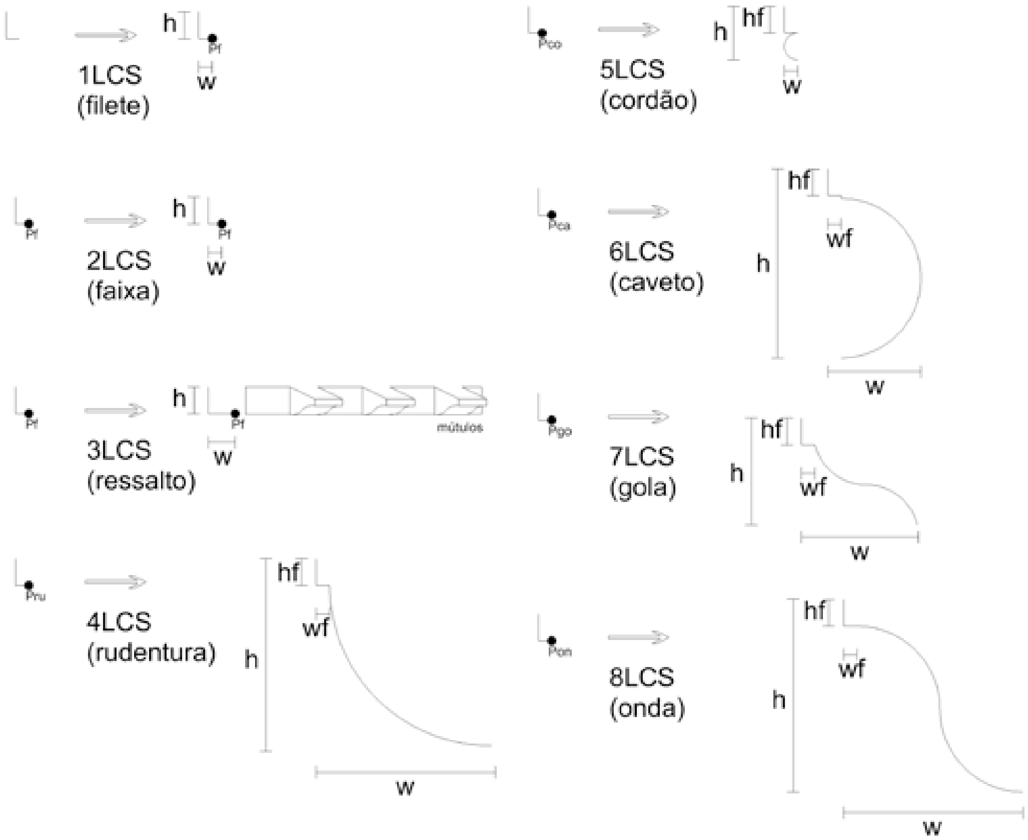


Figure 3
LCS system shape grammar.

dure to generate almost all the column system with a sub system that was embedded in it. Finally another function of the LCS system was to provide a location for decorative elements like flowers, leafs, and eggs, which are not addressed in this paper.

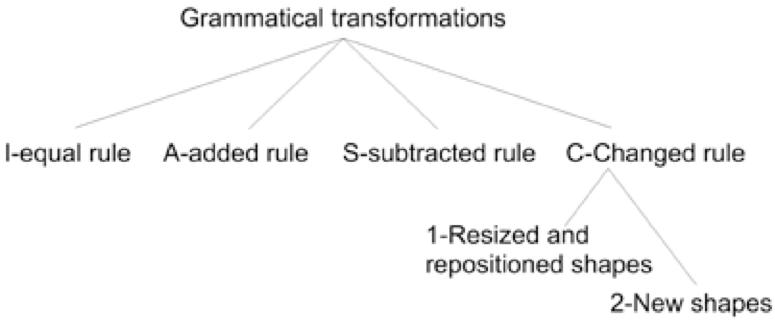
The column systematization shape grammar that can be developed from the LCS system is a grammar of detail and it is identified as a bottom up shape grammar. The results of the experiment described in this paper support this hypothesis. Apparently the rules from the treatise are to be applied in an almost straightforward fashion. But Alberti`s established that the designer must use them as pleased in order to achieve "concinitas", that means according to him quantity, proportion, and location.

The rules in use are rules of the type x→x` defined by Stiny, meaning that a shape x is transformed in a similar shape with parametric variations (Stiny, 2011). If we get rid of the parameterization, we may obtain rules of the type x→y, which transform a shape x into another shape y.

Both x and y are elements in the index of dimensions i and j, where i ∈ {0d, 1d, 2d, 3d}, that is, points, lines, planes, solids, and j ≥i). In the LCS vocabulary, C is part of the base that is part of the column and so on. A general definition of this embedding feature is x→prt(x).

In this particular case, LCS shapes are boundary

Figure 4
Diagram specifying the operations for transforming a grammar.



elements of the columns. Let's take then the definition rule x→b(x) to encode the transformations that occurred in the design of an element from an original grammar to a transformed grammar.

THE GRAMMATICAL TRANSFORMATIONS - EVALUATION PROCESS AND FEEDBACK

One role of the grammar is to help tracing the influence of Alberti's treatise on the design of the São Vicente de Fora church by verifying whether its elements can be obtained from Alberti's rules or some sort of transformation of such rules.

The Transformations in Design framework proposed by Knight (1983, 1994) -- according to which the transformation of one style into another can be explained by changes of the grammar underlying the first style into the grammar of the second -- will be used as the theoretical background.

According to Knight, There are at least four different ways of transforming a grammar as diagrammed in Figure 4, namely, rule addition, rule subtraction and rule changing, which can be designated by letters A, S, and C, respectively. A fourth transformation type I can be added if we consider that a rule can remain unchanged, This transformation I is important for our study because each time such a transformation is used there is strong evidence that the designer was knowledgeable of Alberti`s rules, as seen in the Loggia Rucellai shape grammar by Alberti himself (Coutinho et al., 2013). In the São Vicente de Fora grammar presented in this paper, r2, r4, r5 and r7 ∈ I; r6, r10 and r11 ∈ A; r0, r1,r8 and r9 ∈ C; and r3 ∈ S.

As Knight mentions, in rule change transformations C shapes are defined as transposed shapes, that is, as new shapes or as resized and/or repositioned shapes. Rules 2, 4, 5 and 7 are equal to those found in the original Albertian grammar. In Rule 3 the changes verified are in the constituents of the Capital. The disposition of the capitals are similar to those found on the second level of the Palacio Rucellai's façade. In this case, there is a simultaneous subtraction and resize and reposition transformations. The Shaft, Base and Capital's heights are equal to the ones described in the treatise. Rule 6 adds a new element to the grammar, a barrel vault ceiling. Is to be noted that this element don't belong to the column system. Rule 10 adds a new chapel and Rule 11 the high chorus. Rule 8 and 9 a mirror but changes the axis location. Is to be noted that in the treatise is not specified the notion of mirror but of symmetry. Rule 0 and Rule 1 change the location of labels.

These rules manipulate elements that need to be more closely observed. A technique to recognize and analyze sets of curves was used. This technique consists in a Grasshopper code (Figure 5) whose main goal is to extract and compare section lines from an element of the column (a Doric Base torus), which proceeds automatically in three different steps:

The first step is the extraction of a line section from a mesh surface out of the point cloud.

The second step consists in comparing this

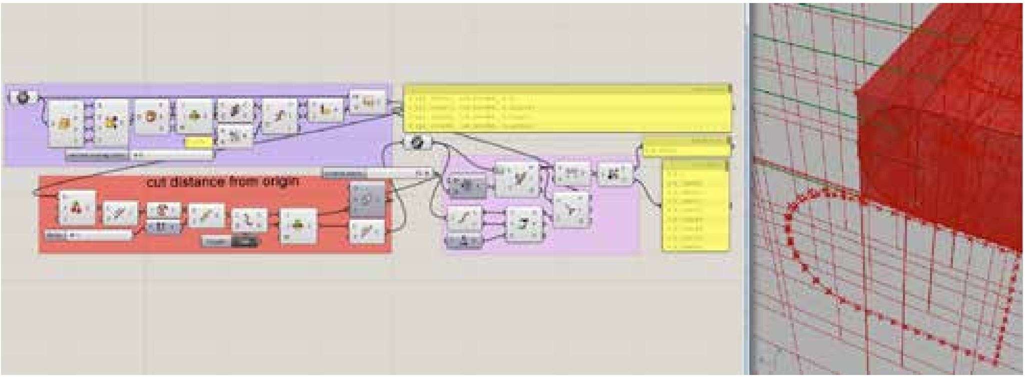


Figure 5
GH code to identify and analyze segments of the column system elements.

line with a curve previously embedded in the code through the distances between the control points of both lines, which need to be bigger than 0. In rule x→b(x), b is such that (in this particular experiment) b>0; and b ∈ B where B ∈ LCS.

Then, the third step analyses the difference in value of linear distance and rejects the ones that are not in the acceptable range. This last stage is not completely implemented yet. A similar process using canonical representation (Keles et al., 2010) graphs are in use in order to better visually understand the differences and similarities between the topology of different lines. As said above, the control points of the target curve and the points of section extracted from the cloud are points contained in parallel lines. The distance measured is the segments of such lines. This process is not completely efficient. It might work well for straight lines contained in parallel planes but not in the case of curves in the 3d space. It is interesting to note that the process used in this experiment reduces the Algebras so that U33 → U12 → U02.

CLOSURE

The contributions of this paper are threefold: first, it is the first Portuguese grammar obtained from Alberti`s treatise shape grammar rules; second, it uses a laser surveying and the resulting point cloud model (PCM) as a way of transforming the grammar and develop the São Vicente de Fora shape grammar; and third, curves that are sections of parts of the "real" building obtained from the PCM are automatically recognized, analyzed and evaluated suggesting that this technique might be an efficient way of evaluating large data sets.

The use of such survey data to generate the grammar was of great help, particularly, considering the level of accuracy and detail that is possible to achieve from such a method.

The code to automate the shape recognition proved to be helpful but improvements are necessary, namely the generation of mesh surfaces directly from the PCM in a complete automated way.

The process for choosing the curves from the corpus (that are the models to be merged) needs to be optimized and is not completely defined. So far a linear distance is in use but the notion of neighborhood (Krishnamurti and Stouffs, 2004) might be of great help in order to understand the kind of transformations occurred in the application of the rules in different buildings. This task will be the focus of a future research article.

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Languages of Design

Combining Complexity and Harmony by the Box-Counting Method

A comparison between entrance façades of the Pantheon in Rome and Il Redentore by Palladio

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Abstract. *When Benoît Mandelbrot raised the question about the length of Britain's coastline in 1967, this was a major step towards formulating the theory of fractals, which also led to a new understanding of irregularity in nature. Since then it has become obvious that fractal geometry is more appropriate for describing complex forms than traditional Euclidean geometry (not only with regard to natural systems but also in architecture). This paper provides another view on architectural composition, following the utilization of fractal analysis. The procedure concerning the exploration of a façade design is demonstrated step by step on the Roman temple front of the Pantheon by Appolodorus and its re-interpretation – in the particular case the entrance front of Il Redentore, a Renaissance church by Palladio. Their level of complexity and range of scales that offer coherence are visualized by the specific measurement method of box-counting.*
Keywords. *Fractal analysis; box-counting method; Pantheon; Il Redentore; Palladio.*

INTRODUCTION

This paper has two objectives:

1. The first one concerns the description of harmony defined by the appearance of architectural elements of different sizes and scale.
2. The second one utilizes the first one, introducing an objective comparison method between an architectural design (acting as origin) and its historical followers.

Apart from an analysis concerning the utilization of characteristic architectural elements, the current study focuses on the overall viewpoint specified by a harmonic expression of distributions across different scales. The author uses for the first time a particular fractal analysis method as measurement of reminiscence, applied to the Roman temple front of the Pantheon (built between 110 and 125 AD by Appolodorus) and the Renaissance temple front of Il Redentore in Venice by Palladio (groundbreaking in 1577) – The Pantheon was chosen as Palladio (1984) emphasized the particular importance of that building. As benefit of the quantitative method, similarity between two façades can be proved with regard to visual complexity.

Fractal analysis

Fractals – the term was introduced by Mandelbrot in 1975 – are characterized by specific properties, which include development through iterations, infinite complexity, roughness, irregularity, scale invariance and self-similarity. The latter is a central feature – although not a guarantee that the structure is fractal – and sometimes, if statistically, difficult to describe. In mathematical terms, a self-similar composition exists, if parts look exactly or approximately like the whole. With variations, however, it is difficult to detect the basic connection between the whole and its parts, or, in other words, to decipher the underlying rules. Characterization is then provided by the Hausdorff dimension – Mandelbrot (1982) calls it fractal dimension – which in the case of a fractal structure exceeds its topological dimension. In addition, according to Bovill (1996), visually, fractal dimension is the expression of the degree of roughness – that is how much texture an object has. With regard to architecture, it specifies the relationship between a building unit on a higher level (larger scale) and its components on a lower level (smaller scale). Throughout this paper, in order to measure the fractal dimension, box-counting – whose result is equivalent to the fractal dimension – is used as fractal analyzing method.

As is described elsewhere (Lorenz, 2012), fractal analysis in architecture ostensibly leads to two different groups:

3. The first one includes buildings with rather smooth façades and a few well distinguishable architectural elements. Such a conception indicates closer relationship to Euclidean geometry.
4. In contrast, the second group comprises buildings with elements of many different scales whose number increases while scale decreases and whose smaller parts reflect the whole through a common idea. An object of this category is, in terms of harmony, a consistent whole, which is reflected in all of its parts – a concept that is rather close to Fractal geometry (Mandelbrot, 1981; 1982).

Harmony and Box-Counting

Harmony fulfills the expectations of the observer for a quantity of new architectural elements on smaller scales that reflect – at least in their roughness – the whole (Salingaros 2006). However, parts need not be exact, scaled down copies of the whole, but should reflect the basic motif or the basic idea with variation (Lorenz 2011). Otherwise the result gets monotonous or in the other extreme confusing. In short, a continuing irregularity is the reflection of a harmonious connection between the whole and its parts (as it is true for a theme in music). Nevertheless, due to the process of building, the intention of the architect and material restrictions, fractal characteristics are, in any case, restricted to a certain range of scales.

The starting-point of our investigation is the definition of a harmonic whole by an appropriate balance between the number of architectural elements of different sizes and the respective scale of consideration. The characteristic values remain the same, irrespective of the considered detail. Box-counting – a fractal analysis method introduced by Mandelbrot (1982) – enables the examination of how characteristics of a structure (details) change with scale. If this method is applied to a façade, this means basically, to translate its two-dimensional representation (the elevation) into a grid-based Pixel image for the purpose of getting the number of boxes that cover the image. This can sufficiently be achieved by placing a grid over the plan in order to count those boxes that contain a significant part of the elevation – represented by lines (Figure 1a). Subsequently, the scaling factor s_i, given by the reciprocal number of boxes in the bottom row of the grid, is reduced and covering boxes N_i are counted again. This procedure is repeated depending on the scale of the plan, i.e. until the detail richness corresponding with the distance of the observer is reached. Finally, in a

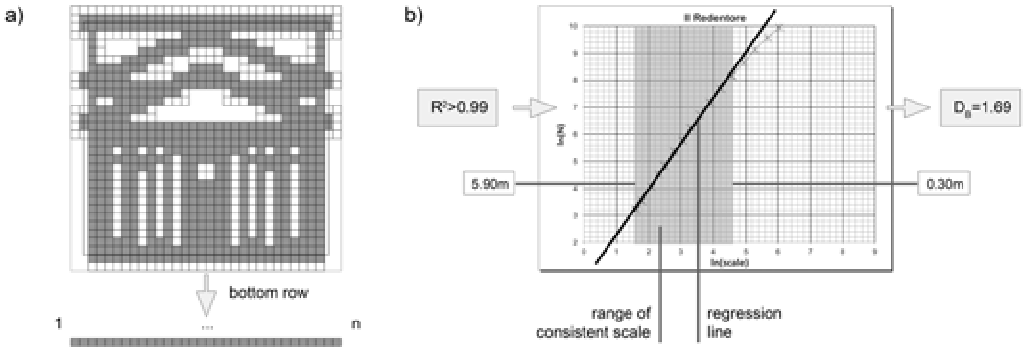

Figure 1
a) Pantheon: A grid is placed over the front view of the Pantheon. Those boxes that cover the composition are colored gray. The reciprocal number of boxes at the bottom row defines the scaling factor.
b) Il Redentore: A given coefficient of determination R^2 leads to a specific range of scale and finally to the box-counting dimension D_B. D_B is equivalent to the slope of the regression line in the graph.

double-logarithmic graph with the number of boxes N_i versus scaling factor s_i, the slope of the regression line defines the box-counting dimension D_B (Figure 1b) for a certain range of scales (Foroutan-pour et al. 1999).

Concerning the box-counting method, a consistent whole across many scales is expressed by a continuing characteristic of complexity, with the characteristic of complexity given by the relation between scale and number of boxes covering the elevation. A small deviation signifies the continuation of a similar irregularity across different scales. Consequently, it is the straight part of the data-curve indicating a harmonious distribution (Figure 1b). The straight part is expressed by a coefficient of determination R^2 close to one. Hence, in turn, with a certain single measurement, the smallest and the largest scale act as limits of the specific range of coherence, derived from a given minimum value for the particular characteristic coefficient (Figure 1b).

Bovill (1996) was the first who applied box-counting to architecture as a method for measuring the characteristic visual complexity of buildings. Since then, it has been used by many researchers (Zarnowiecka, 1998; Lorenz, 2003; Ostwald et al., 2008; Vaughan et al., 2010). Advantages of the method are on the one hand its easy usage (hence its simple implementation) and on the other hand its applicability to any object (with and without self-similar characteristics). Nevertheless, in order to use box-counting as a comparison method, several parameters that influence the result in the one or other way have to be taken into consideration (see section *Influences by Parameters*). Some of them, such as line thickness, have been solved by the author's implementation of the algorithm in a CAAD software (Lorenz, 2009; 2012). Other factors are still unsolved, e.g. the definition of what is measured, concerning the selection of relevant parts of a façade and its translation to a plan (elevation). As a consequence, one part of this paper deals with the application of a fractal analysis method for the purpose of figuring out a correct and efficient way of a grid-based representation of an elevation on plan and of testing the box-counting method implemented in AutoCAD. As a word of notice, plans that are used throughout this paper have been prepared in the same manner to guarantee consistence.

Box-Counting as Comparison Method

Throughout history of architecture, one is confronted with buildings that refer to preceding epochs. Descriptions of visual complexity provide a means for comparison, independent of rearranged components or of changes of the purpose that the respective building is used for (church/villa), meaning that the characteristic values of complexity detect connections between two related buildings. In the specific case, a Roman temple front, the Pantheon in Rome, serves as a starting point, while the Renaissance building Il Redentore in Venice represents its successor. Andrea Palladio, the architect of the latter, used the motif of interlocking different combinations and modifications of classical temple fronts deliberately as a harmonic transition from the entrance view to the dome (Wundram et al., 2004).

The study is based, on the one hand, on the assumption that higher complexity leads to a higher box-counting dimension and, on the other hand, that the harmony of a composition is reflected by a trend of the results, i.e. by a straight line of the data-points in a double-logarithmic graph with grid-scale versus number of boxes that cover the composition (see section *Harmony and Box-Counting*). On this basis, the paper describes a further development of the concept with two aspects as indices of complexity: the box-counting dimension (Bovill, 1996) and the interquartile range (Lorenz, 2012) – i.e., the robust estimate of the variability of the data under consideration gives a valuable description of visual complexity and harmony. This suggests that if the harmonic expression (given by the range of scales) and the height of the characteristic box-counting dimension are similar for the ancient temple and Il Redentore, Palladio's interpretation follows its historic inspiration with regard to harmonic expression.

ANDREA PALLADIO

Palladio's (1508-1580) work is characterized by rediscovering and applying classical Roman architecture – strongly influenced by five travels to Rome conducted in the period between 1541 and 1554, during which he studied classical buildings captured in various drawings. The results of his studies were first published in "L'Antichità di Roma" (Palladio, 2009), a list of preserved and recovered monuments of Rome as they there stand by the mid 16 century. In his book, which is entirely textual, Palladio dedicates more lines to the Pantheon than to any other monument. His views are, however, based solely on existing references. Influences of Palladio's later understanding of form can be deduced from drawings he made of the Pantheon, in which he develops two gables at the same façade (Puppi, 1994). Later, Palladio brought forward the topic of overlapping gables (establishing interlocking architectural orders with a dominant middle order) when commissioned to design the façade of San Francesco della Vigna in Venice in 1562. Finally, both, San Giorgio Maggiore and Il Redentore in Venice, act as results of his continuing development to combine the strict impression of classical temple fronts in a three-aisled church – with Il Redentore providing an obvious relation to the Pantheon (Puppi, 1994).

Andrea Palladio and Venice

Palladio's first assignment in Venice, and moreover, his first practical work on a church was the redesign of the façade of San Pietro in 1558. However, it was not executed before 1594 – presumably because of the commissioner's, the Patriarch Vicenzo Diedo, death and in a modified form (Puppi, 1994). The first design Palladio actually executed in the city of Venice was the Convento della Carità (convent of Santa Maria della Carità), the construction of which began in 1561. The concept is based on a Roman house transformed into monumental scale. While the atrium and a cloister beyond it consist of a Corinthian order, the inner court represents a vertical stacking of three different orders, with the Doric at the base, the Ionic in the middle and the Corinthian at the upper level (Society for the Diffusion of Useful Knowledge 1840).

In the city of Venice, Palladio, well entrusted with designing villas and palazzos, finally could translate classical orders – which he regarded as the embodiment of beauty – to two churches. At first he got the commission for San Giorgio Maggiore situated on San Giorgio di Castello in 1564. The front façade, which is composed by two different reminiscences of classical temple fronts, was finished 30 years after his death (in 1610). The front façade is dominated by its middle part, the entrance, consisting of four three-quarter columns of Composite order on high pedestals, supported by a pediment. The second temple front covers the church aisles by two halves of a pediment. Visually it continues behind the first temple front which is supported by the use of pilasters (of Corinthian order) instead of columns. Both sides are nevertheless held together by the horizontal entablature (especially the cornice), which continues along the main temple front while the upper part of the tympanum is interrupted. Moreover, the pilasters of either side of the entrance belong to the second temple front. Finally, decoration is only found with columns, entablatures and niches.

Il Redentore – composition and architectural elements

Towards the end of his life, Palladio was commissioned to plan his second church in Venice, Il Redentore, situated on the island of La Guidecca. The erection of the (procession, monastery and) votive church was decided after Venice had been visited by a plague in 1575, which killed forty thousand of the citizens. The construction work began in 1578, only two years before Palladio's death. Concerning urban planning, the task was similar to San Giorgio Maggiore in setting up a connection between the new church and Piazza di San Marco across the water. The composition of Il Redentore is similar to San Giorgio Maggiore in so far that the dominant middle part of the front view is formed by a large Composite order, while a broader Corinthian order supports the flanking aisles as a transition to the high middle nave. Both façades provide reminiscence of interrelating Roman temple façades and are characterized by simplicity in the ornaments. Differences only become obvious on closer view. Concerning Il Redentore, the middle order is placed on a higher platform and consists of lower pedestals (which look more familiar). Moreover, while the dominant temple front of San Giorgio Maggiore consists of four three-quarter columns of Composite order, the entrance of Il Redentore is flanked by two half-columns of larger intercolumniation followed by one pilaster on each side (both again of Composite order). The middle dominant front does no longer appear to stand free (as the wall behind continues above the gable). Another difference concerns the position of the horizontal cornice of the smaller order which is in the latter case much higher in relation to the columns and pilasters of the middle order. While at San Giorgio Maggiore this architectural element was continued along the dominant temple front (behind the cut off columns), it is now interrupted and only continues in form of the pediment supplementing the entrance. This time, the pilasters of the second order are protruding in the middle part in the form of two half columns flanking the entrance. Moreover, the intercolumns change from broad, narrow, broad, narrow, broad in the case of the earlier church to a more harmonic sequence of narrow, narrow, broad, narrow, narrow in the case of Il Redentore. The frontal view of Il Redentore provides a third temple front formed by the upper part, including the backwards sloping roof as pediment and the side parts sweeping the aisles.

FRACTAL ANALYSIS

Methodologically, the author follows the box-counting algorithm described in Lorenz (2009; 2012). As noted elsewhere (Lorenz, 2012), results are either influenced by the transformation of the façade into a plan – hence, the preparation of the plan – and by certain factors that are coming along by the method itself (Foroutan-pour et al., 1999). In consequence of the transformation into a plan and to ensure consistency in analysis, the author considers vector-based re-drawings of both façades concerned in this paper.

Influences by Parameters

One of the most crucial aspects influencing the result is the choice of significant parts of the elevation – i.e., translating the façade into a black and white plan (Lorenz, 2003; 2009). In consequence, the choice of represented architectural elements has to be defined unambiguously, referring to the visual perception (Bovill 1996; Lorenz, 2003; 2009), and justified carefully. Bovill (1996) refers to Maertens (1884) when defining the relation between distance and smallest detail (Lorenz, 2009). The smallest detail, for instance, is influenced by the reading field, that is the minimum size of clearness of seeing within an eye angle of 0°1'. In addition, Märtens distinguishes between three distances of observation that correspond to the scale of the façade (in meters). The first one includes the environment (deduced from a viewer's position of 18-20° of building height), the second considers the whole building (27° of building height) and the third one focuses on details (45° of building height). The present measurements correspond to the second and third distance. From a distant view, only main parts of the design are perceived and consequently taken into consideration. Beside the silhouette, this includes columns, the gable, main parts of the entablature (architrave and cornice), but no detail of the capitals. The latter belongs to a closer distance of observation.

The experimental set-up not only includes the selection of lines, but also the definition of the smallest and largest box-size. While the smallest box-size depends on the smallest detail and is reflected by the point where the data curve calculates only the single lines of the elevation ($D_B = 1$), the largest box-size should be one fourth of the smallest side of the measured image. Other influences include the relative position of the grid, the orientation of the grid and the reduction factor of the grid. With a reduction factor of one half, the number of boxes at the bottom row doubles for the next smaller grid-size.

Implementation

The author's implementation of the grid-based box-counting algorithm into AutoCAD uses vector-based geometries in a tool architects are used to. The script allows various options, which are available in form of tabs:

- *Selecting the area for measurement*. If the area contains the image completely, the bounding box serves for further calculations, otherwise it is cut.
- *Defining specifications*. This includes, for example, the number of iterations (how often the grid-size is reduced), the enlargement factor (percentage of empty space around the selection area), the number of steps between two scales (the reduction factor – which is defined as the ratio of how much the grid-size is reduced from one step to the next – is defined by one half; by inserting a number of steps between two scales the factor is changed to 1/4th, 1/8th and so forth) and the number of boxes at the smaller side (from which the initial grid-size is deduced). Furthermore, for the purpose of accuracy the number of displacement in x- and y- direction can be defined. The number of covered boxes of a certain box-size is then given as the minimum number of all replacements of one and the same grid-size.
- *Changing settings of layout*. This includes drawing a copy of the measured segment and assigning this segment to a corresponding layer.

A second modified algorithm does not start from a reduction factor of one half but takes into account that the difference in box-size between two successive grid-sizes is larger as the scale size increases. Consequently, the user can adjust accuracy by a value that defines the addition of boxes from one scale to the next, where the number of added boxes increases with smaller scales.

Finally, the data, coming along as text-file, is estimated by means of statistical methods, specifically by linear regression. With this technology, a regression line is to fit the logarithmically transformed output of grid-scale versus number of covered boxes. In the particular case, the analysis of the data is done in a spreadsheet program, again supported by a special script. For evaluating the relation of the regression line with regard to the measurement points, the coefficient of determination R^2 is used. The range of R^2 reaches from 0, indicating no relation, to 1, which means highest possible correlation. As more than one measurement is used for analysis (see section *A Set of Measurements*), the range of scales can be adopted for the whole set, resulting in a minimum and maximum coefficient of determination R^2. Only if both, the minimum and the maximum are close to one, the result is called 'consistent'. Otherwise, the regression line does not fit for single results, indicating higher diversity.

A Set of Measurements

It could be demonstrated elsewhere (Lorenz, 2009; 2012) that different measurements lead to different results, due to influences of several parameters coming along with the box-counting method. Therefore, a set of measurements is necessary, rather than a single one. Accuracy is then expressed by the interquartile range of the box-plot (containing 50% of all values). The smaller this range, the smaller is the fluctuation of data-points (single box-counting dimensions) and the more meaningful is the result. The characteristic values are therefore

- the range of scale, given by the smallest and largest box in meter,
- the median, as a characteristic for roughness and
- the interquartile range, as indication of variation.

In turn, a given coefficient of determination leads to a specific range of coherence for a whole set of measurements and, following from that, to a definitive value by the median of the data (Lorenz, 2012).

ELABORATION

To ensure the required conditions of the author's implementation of the box-counting method, a vectorized representation of the real façade Il Redentore is considered. As statues were added only in the second half of the 17th century (Wundram et al., 2004), they are excluded from measurement, as well as small details including the shaping of capitals. In general, the selection includes main design elements according to a distance from where the building is perceived as a whole (see section *Fractal Analysis*).

In order to minimize potential sources of error, both algorithms are used – dividing the grid by one half (set A) and adding boxes for each step (set B) – with 11 different configurations in each case. The configurations include:

- the factor of enlargement (either one, three or five percent of minimal side length),
- the number of starting boxes in x-direction (either three of four),
- depending on the algorithm, either the number of steps between two grid-sizes (none, one, two or three) or the factor of accuracy (three or four) and
- the number of replacements in x- and y-direction (one by one or three by three).

The interquartile range and the coefficient of determination are the basic instruments of evaluation of the results: While the first value is related to the whole set, single measurements are taken into account by the second criterion. In particular, the latter is specified on the one hand by the minimum R^2, which tells us about the most deviating result of a whole set, and, on the other hand, by the average R^2, which describes the general fluctuation of data of all measurements.

When discussing the results of measurements it is conspicuous that for any single measurement of Il Redentore, the coefficient of determination exceeds 0.996 (0.997), which is very close to one, proving that each regression line fits the data well (minor deviation). Finally, the spectrum of the resulting box-counting dimensions (slope of the regression line) is shown in a box-plot, separately for set A and B (Figure 2a). The respective small interquartile ranges express high accuracy of all data: For set A it is 1.89 percent (in relation to two as possible results in a two-dimensional space are between 0 and two) while for set B it does not even exceed 1.5 percent. Finally, the median of each set – that is the break line where 50 percent of all values can be found above and below respectively – equals 1.677 and 1.685. From these results, it can be deduced that the façade of Il Redentore is of high complexity, with a consistent use of architectural elements from the whole to a very small scale (Table 1).

As shown in Table 1 the results of both algorithms are very close with slightly higher accuracy of the gradual increase of boxes, i.e. set B (higher min R^2 and smaller interquartile range).

DISCUSSION AND COMPARISON OF RESULTS

Because of its importance for Palladio (see section *Andrea Palladio*), it is the Pantheon in Rome that serves as a reference object. For analysis, two sets (A and B) of 11 measurements each are carried out.

Il Redentore			
Median		1.677	1.685
Interquartile range		0.038 (1.89%)	0.029 (1.45%)
Minimal R^2		0.996	0.997
Average R^2		0.998	0.998
Range of coherence			
	Maximum box-size	7.93 meters	8.46 meters
	Minimum box-size	0.32 meters	0.31 meters
Range in % of the height of the front view			
	Maximum box-size	29.95 %	31.95 %
	Minimum box-size	1.20 %	1.16 %

Table 1
Il Redentore: Results of measurement; Left: dividing by half; Right: adding boxes.

Despite differences of overlapping elements, the results nevertheless display a similar range of coherence in comparison to Il Redentore (Table 2 and Figure 2b). Moreover, the medians of the two sets are similar to Il Redentore: the median of set A equals 1.661 (1.677) and for set B it is 1.660 (1.685) – with slightly higher interquartile ranges of 2.07 and 1.32 percent. This leads to the conclusion that both façades are characterized by a similar development of architectural elements across a similarly broad range of scales (range of coherence: 1-30 percent with Il Redentore and 1.5-28 percent with the Pantheon). In particular, this means that details of a certain size have their correspondence in both façades, although differences in design are obvious. E.g., Il Redentore, for instance, displays not only one but two clearly interrelating Roman temple façades, while the Pantheon consists of two vertically arranged gables. In the case of Il Redentore, niches for statues and the pillars flanking the entrance with own gables display another additional level.

Concerning the different algorithms, both sets of measurement lead, as it is true for Il Redentore, to very similar results (Table 2). The deviation of the data is again low, although this time minimum R^2 is slightly lower (0.992 and 0.994) than in the case of Il Redentore (0.996 and 0.997).

CONCLUSION

The box-counting method provides an objective comparison method between design solutions demonstrated by Il Redentore and the Pantheon. It visualizes the development of roughness across multiple scales and, derived from that, the harmonic relations between the whole and its parts. Both results discussed in this paper show a similar depth of details and a similar level of complexity. Specifically, this means that, even if Palladio changes the com-

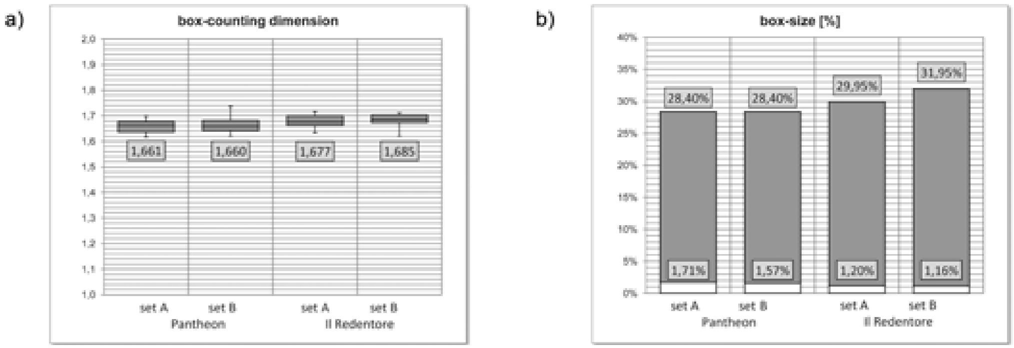

Figure 2
Il Redentore and Pantheon: box plot diagram of box-counting dimensions (a) and box size in percentage of the height of the front view (b).

Table 2
Pantheon: Results of measurement. Left: dividing by half; Right: adding boxes.

Pantheon			
Median		1.661	1.660
Interquartile range		0.041 (2.07%)	0.026 (1.32%)
Minimal R^2		0.992	0.994
Average R^2		0.994	0.995
Range of coherence			
	Maximum box-size	9.10 meters	9.10 meters
	Minimum box-size	0.55 meters	0.50 meters
Range in % of the height of the front view			
	Maximum box-size	28.40 %	28.40 %
	Minimum box-size	1.71 %	1.57 %

position of the temple front, the harmonic distribution across all scales is similar to the Pantheon. This proves that, although variations in the reinterpretation occur, Il Redentore nevertheless takes up the same characteristics as its origin of a Roman temple front.

Box-counting reveals similarities and differences between styles with regard to different degrees of roughness and depth of self-similarity. Up to now, the author has analyzed façades, corresponding to a larger distance of the observer. As ornaments are characteristic elements of a building, it would be interesting for future work to deal with a smaller distance as well.

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The Rehabilitation Design Process of the Bourgeois House of Oporto: Shape Grammar Simplification

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Abstract. *This study was accomplished in the context of a broader research to be developed in an ongoing PhD program in architecture. The purpose of this study is to give a perspective of the research progress and to present a shape grammar simplification that will be improved to assist the rehabilitation design process of the bourgeois house of Oporto.*
The typology of the bourgeois house of Oporto, built from the late sixteenth century until the early twentieth century, is dominant in the ancient fabric of the city and in need of rehabilitation. From the analysis of a representative sample of a moment of its evolution, it is possible to verify patterns and to define rules.
This first approach intends to validate the use of shape grammars as a tool, able to assist the architect in the rehabilitation design process of the bourgeois house of Oporto.
Keywords. *Design process; rehabilitation; shape grammars.*

INTRODUCTION

The overall goal of the ongoing PhD is the development of a tool able to assist the architect in the rehabilitation design process of the bourgeois house of Oporto, Portugal. The research described in this paper start this with the presentation of a shape grammar simplification focused only on the topology of rehabilitated or in rehabilitation buildings.

The old center of Oporto should be preserved not only for the knowledge and symbolism present in its built historic heritage, but also for its intrinsic material and economic values.

In this city, the Porto Vivo, SRU - Society for Urban Rehabilitation has recently been created and its mission is to lead the process of urban regeneration. This institution has replaced CRUARB (commission for the urban renewal of Ribeira/Barredo) restructuring their political action.

According to the Management Plan for the Historical Centre of Oporto, a strategic document created in 2010, a requirement of UNESCO, when it revised its classification program of world heritage sites, the historical center consists of 1,796 buildings, 443 in good condition, 649 in average condition, 575 in poor condition and 78 in ruins, with 51 being works in progress. The dominant function is housing, constituting 80% of the buildings (Loza, et al. 2010). The bourgeois house is the building type that predominates in this territory.

In the critical success factors in the report of the 2010 activities of the SRU, we can identify as weaknesses the extent of the territory and the complexity of the task and as strengths the experience, knowledge and results.

The report of the 2011 activities emphasizes the experience gained during its seven years of existence. The report of 2012 given the economic context and the restrictions on access to bank credit estimates more constraints to the rehabilitation process.

At present the urban regeneration in the city of Oporto is seen as an objective in the medium, long term.

Architecture is an open work and should not be regarded as an achievement but as a process, it is never finished and is continuously used (Vieira de Almeida, 2008).

The bourgeois house of Oporto has been the subject of some interventions which resulted in the accumulation of a niche of experience. In the vast work still to be done it is important to understand how this experience can be used efficiently.

With the intention of supporting the rehabilitation design process of this buildings, a shape grammar simplification was developed based on the information extracted from a sample of rehabilitated or in rehabilitation buildings. This study validates the use of shape grammars in the analysis of the design solutions used for this buildings and in the creation of new solutions in the same language.

THE BOURGEOIS HOUSE OF OPORTO

The house is an elementary part in the conformation of the streets and in the fabric of the city as a whole. In Oporto the high narrow house (Figure 1), originated from the old borough, prominent in the old heart of the city and in the streets that radiated from him, continued the local tradition, assimilating successive styles and techniques (Oliveira and Galhano, 1992).

In Oporto there is an apparent lack of uniformity in their houses, different shapes, sizes and colors mark the first impression you may have.

A closer look identifies two fundamental types. The high narrow house with three or four floors, sometimes reaching the five floors with two or three openings was in origin a hybrid type. Congregating residence with commercial activity, belonged to the bourgeoisie, had stores, warehouses and workshops on the ground floor and housing on upper floors (Figure 2). Among them, rarer, large and low houses composed mainly of ground-floor and main floor with numerous façade doors and windows was the noble house with large spaces as a statement of prestige and power in the city (Oliveira and Galhano, 1992).

The two fronts bourgeois house set in a Gothic-mercantile lot has taken origin in the duplication of smaller lots of only one front houses. Those houses of the oldest part of the city, raised in narrow and deep lots, adherent to the existing relief, are an urban and architectural fact immediately associated to Oporto (Barata Fernandes, 1996).

These houses persisted in local tradition and followed the evolution of the city from the late sixteenth to mid-nineteenth century and kept some of their basic features to the early twentieth century.

Figure 1
Street Clérigos (author's photograph).

Figure 2
Street 31 de Janeiro (author's photograph).

This type of house is not exclusive from Oporto and it is possible to establish relations with other European cities such as Genoa, Bologna, Pavia and Florence or even cities of northern Europe (Barata Fernandes, 1996).

The bourgeois house of Oporto for its dominance and symbolism presents itself as a key element in the rehabilitation of the built historical heritage of the city. Over time it becomes important to reevaluate their internal organization and uses, materials and building construction system, in a gesture to rescue the past and strengthen its basic features.

THE SHAPE GRAMMARS

The first publication of shape grammars goes back to 1972 and had as authors George Stiny and James Gips (1972). In an early stage, it was applied in the interpretation and evaluation of pictorial works. Later in 1980, with the publication of the paper "Kindergarten grammars: designing with Froebel's building gifts", George Stiny (1980) presents a grammar defined in the three dimensional space that was the initiator of the architectural grammars that followed.

Shape grammars can be defined as algorithmic systems for creating and understanding designs directly by computing shapes, instead of text or symbols. A shape grammar is a set of rules that are applied step-by-step to generate a language of designs [1].

Shape grammars are descriptive, analytic and generative: descriptive because they explain the formal structure of the designs that are generated, analytical because they can be used to tell whether a new design is in the same language, and generative because they can be used to create new designs in the language (Stiny & Mitchell, 1978).

In 1976, George Stiny demonstrated that shape grammars can be original or analytical when applied to the creation of new design languages or in the study of existing ones (1976). According to Terry Knight [1] this gesture was the basis for new approaches and an enhancer of its use in education and practice.

The analytical studies are based in a set of existing designs that represent the language - the corpus - used to infer the rules of the grammar, which is then tested by using the rules to generate designs in the corpus, as well as new designs in the language.

George Stiny (1981; 1992) has also shown that shapes, labels, and weights can be combined to form shape grammars that encode specific languages of designs.

The shape grammar simplification that will be presented follow the steps of the analytical studies and is based on the Malagueira simplification grammar of José P. Duarte (2004). It differs from this one because it not only aims to introduce a more complex grammar but also serves to explore, in a flexible way, different possibilities of developing the grammar for the rehabilitated or in rehabilitation buildings of the bourgeois house of Oporto. Unlike the Malagueira simplification grammar, the lots and the buildings have different dimensions and uses weights in a different representation to highlight future intentions.

THE CORPUS OF DESIGNS

The theoretical support for this research consists in the study of a moment in the evolution of the bourgeois house of Oporto since the late sixteenth century to the early twentieth century.

The bourgeois house of Oporto has been the subject of some interventions in the historic center and in parts of downtown. The collection of information led to the identification of five different house designs that constituted the corpus for the grammar.

This collection was made taking into account some examples of rehabilitated or in rehabilitation nineteen century buildings that in their origin were from the hybrid type, congregating residence with commercial activity, with warehouses and workshops on the ground floor and housing on upper floors.

Two fronts buildings, raised in narrow and deep lots, with four or five floors, three openings and yards with some variations. The central staircase was structuring in the internal organization, the ground floor had a separated entering from the rest of the building. The functional organization of the housing part of these buildings, in their origin, was not specialized, with exception of the living room located in the front of the first floor and the kitchen that it was always placed in the back of the last floor near the roof (Barata Fernandes, 1996).

The buildings analyzed have been adapted over time to the needs of its dwellers, but they kept same of their basic features to the present day.

Over time, the bourgeois house of Oporto was able to adapt to new circumstances and techniques and became prevalent in the city (Oliveira and Galhano, 1992).

The five rehabilitation solutions studied, divide the buildings in small apartments that are organized respecting the location of the central staircase in a logic that separates the front from the back of the buildings. The ground floor with is own entering continued, in some cases, the commercial activity.

With the study of the rehabilitation designs of this buildings it was possible to verify patterns and to define rules in the definition of a grammar focused on the topology of the bourgeois house of Oporto buildings in the corpus.

THE SHAPE GRAMMAR SIMPLIFICATION

The bourgeois house of Oporto shape grammar simplification combines shapes, labels, and weights to encode different ways of seeing and describing designs.

This grammar is defined in the Cartesian product of algebras U12 V02 and U22 V02 in the two-dimensional representations of the different floor plans.

The decisions made in the organization of the lower floors can condition the generation of the upper floors, this dependency is encoded into the grammar through the use of sequential, parallel grammars, one for each floor.

The derivation of a design in the grammar goes through several successive stages defining each floor. When the generation of a lower floor finishes, the state changes, thereby activating the generation of the upper floor. Each of these stages, in turn, includes several steps, as locating functional zones, locating the staircase and dividing functional zones into rooms.

This simplification is composed by rules for the manipulation of simple geometries representing rooms by dissecting, connecting, extending and adding new shapes to them, as well as rules for assigning and changing functions associated with them.

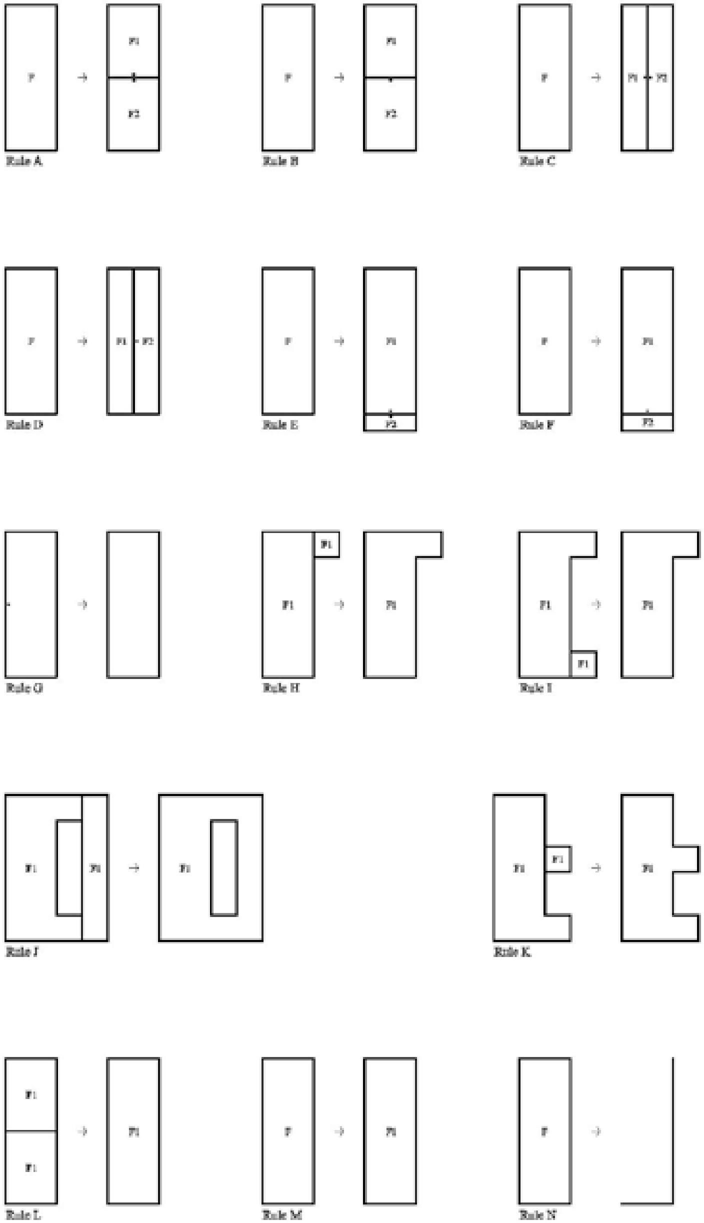
A very simplified set of rules will be presented only with the two dimensional information, where lines represent walls and shaded areas and labels represent the functions associated to the different rooms. The functions of the rooms that the shapes represent are indicated by the labels fn (n = 1, 2). The identification of the last line placed and the indication on which side the next dissection may occur is made by the label dot (•): on both sides (rules A, C and E) or only in one side (rules B, D and F). In rules A and B, dissections are perpendicular to the bigger edge of the rectangle. In rules C and D dissections are perpendicular to the smaller edge of the rectangle. Rules E and F add a new rectangle. Rule G deletes the label •, preventing further dissections. Rules H, I, J, K and L concatenate two adjacent shapes to form a larger room. Rule M assigns a function to a room. Finally, rule N subtracts two lines of the rectangle (Figure 3). The generation of basic layouts, obtaining different patterns, with these rules comprises three steps. In the first step, the lot is divided into different functional zones - yard, working, service, circulation, living and sleeping or living/sleeping. In the second step, the vertical circulations are located. In the third step the functional zones are divided into rooms to obtain the final layout.

A diagram in the form of a tree, in which it is possible to recognize the basic patterns behind the houses in the corpus is shown in Figure 4.

This diagram is composed by nodes representing the state of the design and by arcs representing the application of rules in the definition of the functional organization of the first floor.

A case study will be presented showing the several steps referred above in the first floor derivation of one building in the corpus.

Figure 3
Shape grammar simplification rules.



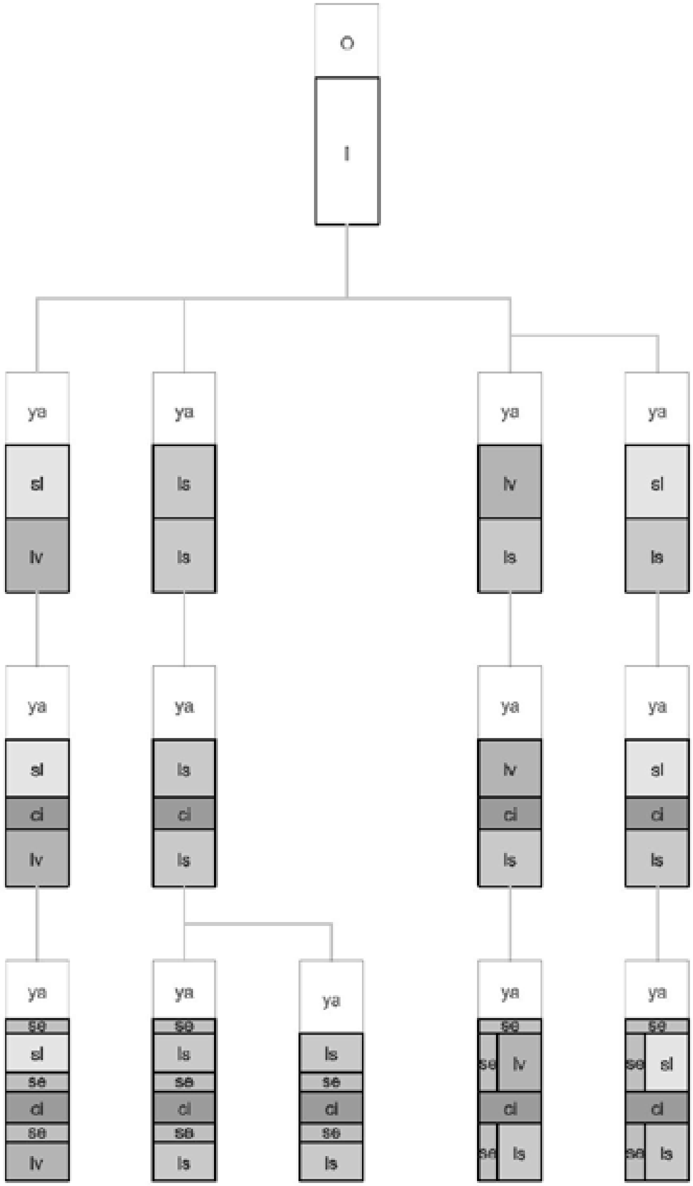


Figure 4
Tree diagram showing the definition of the functional organization of the first floor. I - inside; O - outside; lv - living zone; sl - sleeping zone; ls - living / sleeping zone; ya - yard; ci- circulation zone; se - service zone.

CASE STUDY

The example of an Oporto nineteen century building located in the Almada Street is presented (Figures 5, 6 and 7). The author of the rehabilitation design is the well-known Souto de Moura.

The existent layout and the design proposed by the architect for this floor are shown with the first floor derivation in Figure 8. This floor is organized respecting the location of the central staircase with an apartment in the front and other in the back of the building. Secondary vertical circulations are added. The back apartment also occupies a part of the second floor.

CONCLUSIONS

The purpose of this paper has been to present the first approach to the shape grammar for the rehabilitation of the bourgeois house of Oporto, explaining the reasoning behind this work in progress.

With the intent of supporting the rehabilitation design process of the bourgeois house of Oporto, being aware of the actual rehabilitation context of Oporto and based on "best practice" procedures in heritage conservation, this study not only reintro-

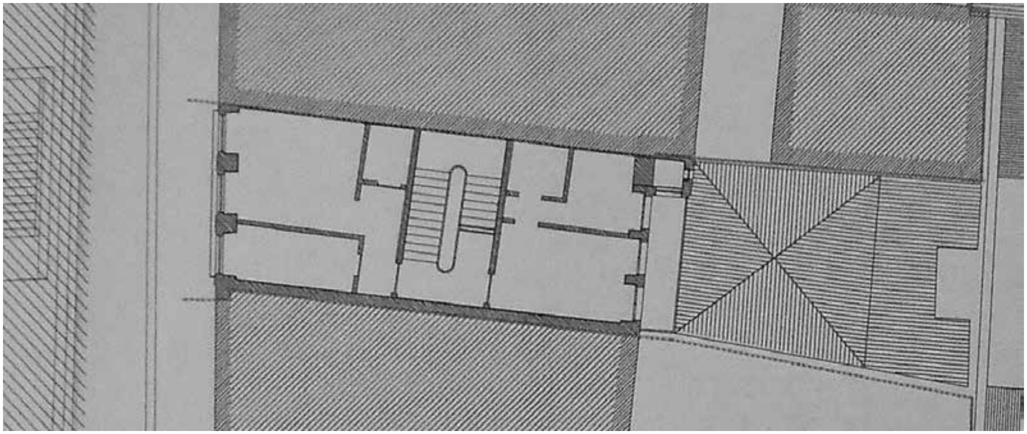


Figure 5
First floor existent layout.

Figure 6
First floor proposal layout.

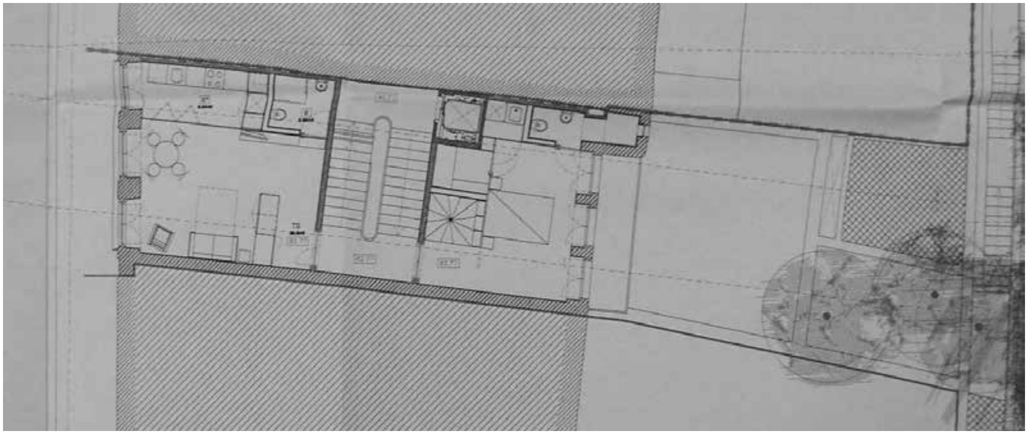


Figure 7
Second floor proposal layout.

duce the discussion of the design process in architecture but also serves to explore a more efficient way to assist the architect in the rehabilitation of these buildings.

This shape grammar simplification was based in the derivation of five rehabilitation proposals and was tested in two new designs in the language. The derivations were useful in the definition of the rules and in the viewing of the shape grammar future development. The new designs served also to update the grammar that is constantly evolving. This approach proved to be proficient in the study of the buildings topology.

A more complex shape grammar is now being developed. It will be parametric and will encode information on dimensioning, on function and on the building system.

This information can be useful to establish the link with BIM (Building Information Modeling). In this approach BIM represents the overall method of handling building information, and not the computer implementations. The possible combination of shape grammars and BIM is being considered.

A shape grammar for the rehabilitation of the bourgeois house of Oporto has been initiated, carving a path for the future development of a new approach to the rehabilitation design process of these buildings.

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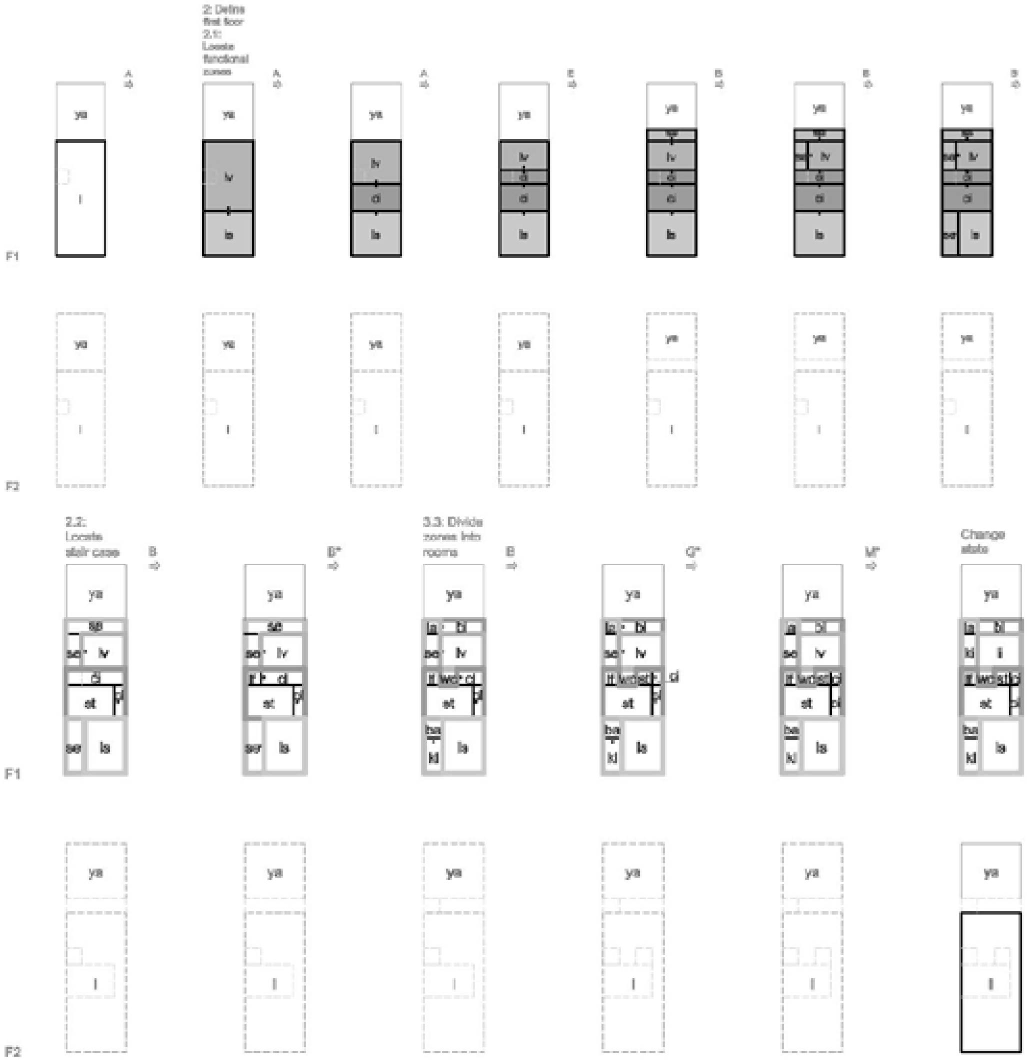
Figure 8
Derivation of the first floor functional organization.
bl - balcony; ba - bathroom; cl - closet; ki - kitchen; la - laundry; lf - lift; li - living room; ls - living sleeping zone; st - staircase; wc - water closet, ya - yard.



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Albertian Grammatical Transformations

From the treatise to the built work in the design of sacred buildings

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Abstract. *This paper presents a research on the use of shape grammars as an analytical tool in the history of architecture. It evolves within a broader project called Digital Alberti, whose goal is to determine the influence of De re aedificatoria treatise on Portuguese Renaissance architecture, making use of a computational framework (Krüger et al., 2011).*
Previous work was concerned with the development of a shape grammar for generating sacred buildings according to the rules textually described in the treatise. This work describes the transformation of the treatise grammar into another grammar that can also account for the generation of Alberti's built work.
Keywords. *Shape grammars; parametric modelling; generative design; Alberti; classical architecture.*

INTRODUCTION

The research described in this paper is part of a larger project called Digital Alberti, whose aim is to determine the influence of Alberti's treatise *De re aedificatoria* on Portuguese Renaissance architecture, making use of a computational framework (Krüger et al., 2011).

This paper analysis the task of achieving a shape grammar that can contribute for clarifying the influence of Alberti's work on Portuguese architecture of the counter-reform period. Previous work was concerned with the translation of *De re aedificatoria*'s descriptions of sacred buildings into a generative shape grammar. (Duarte et al., 2011; Figueiredo et al., 2013) This grammar has shown to be successful in deriving solutions in the same language. However, certain features of Portuguese classical churches are not identifiable in such solutions and, therefore, its source of inspiration remains uncertain.

Several scholars in the history of Portuguese Renaissance architecture report that Portuguese royal house contracted Italian architects and promoted the visit of Portuguese architects to Italy during the 15th and 16th century. (Moreira 1991, 1995; Soromenho, 1995; Branco, 2008) This fact may have caused architects who worked in Portugal during that period to contact with Alberti's buildings that were erected in the late 15th century.

This fact led us to consider the transformation of the shape grammar (Knight, 1983) for generating sacred buildings according to the rules textually described in the treatise, into another grammar that could account for the generation of his built work, namely, its morphological and proportional features.

This paper presents the methodology used to transform the initial treatise grammar into a grammar that can unveil the origin of certain features of Portuguese Renaissance architecture.

METHODOLOGY

A previous grammar, directly inferred from the reading of *De re aedificatoria*, was considered for this research (Duarte et al., 2011). Their rules are mainly described on Chapters IV and V of Book 7 – *Ornament to Sacred Buildings*, where the treatise expresses in algorithmic terms the knowledge base for the design of sacred buildings – temples.

In accordance with the objectives described in the introduction above, the approach followed in this research included four steps: (1) to analyze the most representative sacred buildings by Alberti, with the aim of identifying morphological and proportional features that were not encoded by the treatise grammar; and subsequently synthesizing that information in parametric schemas; (2) to introduce the knowledge encoded by the parametric schemas in the grammar, by changing existing rules or adding new ones; (3) to determine the relation among these rules, the grammar's recursive structure, and the process of derivation solutions in the language; and (4) to translate the grammar's principles into a parametric computational model that allowed one to evaluate the generative outcome of the grammar in a different generative paradigm.

FROM ALBERTI BUILDINGS TO GRAMMAR TRANSFORMATION

The first task in this research was focused on the analysis of Alberti's designs of sacred buildings. Namely, the church of Sant'Andrea in Mantua, rebuilt according to Alberti's 1470 design for Ludovico Gonzaga; the church of San Sebastiano in Mantua, 1460, designed in a Greek cross plan, in consonance with Antonio Labacco drawings (Tavernor, 1996, p.128), to which Alberti planned the construction of a dome in the central space, instead of the existing coved vaults; the external walls of the church of San Francesco, known as the Temple Malatestiano in Rimini, begun in 1453, unfinished, and mainly rebuilt after being severely damaged during World War II; and finally, the facade of Santa Maria Novella in Florence (1458–70) which resulted from a commission of the Rucellai family.

The sources of the drawings used in this task were the photogrammetric surveys done by the Olivetti Group [1] for the exhibition held in Palazzo Te, Mantua in 1994. These drawings were chosen because they do not include later modifications in the buildings layout and architectural details, which can then be considered more loyal to Alberti's design intentions. The first step in accomplishing this task was to collect data identifying Alberti's contributions for the design of each of the buildings (Borsi, 1989; Tavernor, 1998; Rykwert and Angel, 1994).

Following to this, drawings of the buildings were analyzed with the aim of identifying morphological and proportional features that have not been considered in the treatise grammar. Two complementary analysis were performed.

The first analysis was to fill in a survey in which entries collect the buildings' features taking in account the parts of sacred buildings described in the treatise grammar. This information was registered on tables gathering the parameters, conditions and spatial relations translated from both the treatise and the buildings thereby allowing to identify similitudes and deviances between them.

The second analysis was to draw schemas that were useful for synthesizing the buildings' proportional principles, and to identify morphological features that were absent in the treatise's descriptions.

Due to the space restrictions, this article focuses on the analysis of Sant'Andrea's plan. The result of this analysis is synthesized in the Table 1, which synthesizes a survey comparing Sant'Andrea's features with those described in the treatise and in

Table 1
Excerpt from a table summarizing the analysis of the morphological features and proportions of Sant'Andrea's plan. Green rectangles mean that the feature is contemplated in the grammar, while red rectangles mean that it is new to the grammar.

PLAN					
Cell Proportion *(Li : Wi)* *li - area lenght* *wi - area widht*	.1:1	.3:2	.4:3	.2:1	.3:1
Tribune	True	False			
Opening *(We : Wi)* *wi – area widht* *we - chapel widht*	.1:2	.2:3			
Geometry/Shape	REC	CIR			
Proportion *(Lc : Wc)* *lc - chapel lenght* *wc - chapel widht*	.1:1	.1:2			
Lateral Chapels	True	False			
Number *Ncl*	2	6	10		
Geometry/Shape	REC	CIR	REC/CIR	CIR/REC	
Opening/Width *(We : Wcl)*	.1:1 falta informa	.1:11/12			
Lenght *(Lcl : Wcl)* *Lcl - lateral chapel lenght* *Wcl - lateral chapel widht*	.1:1	.1:2			
Skeleton *(Wcl: Ws)*	(1:1/5 , 1: 1/3)	1 : 1/2	√3 : √2		
Wall Thickness *(We:Tw)* *we - temple widht (external)* *tw – wall thickness*	.1:12 *sem capelas*	.1:9	.1:28 *com capelas*		

Figure 1, which diagrams Sant'Andrea's plan proportional schema. Both analyses revealed three main aspects that differentiate Sant'Andrea's plan from the treatise grammar generative outcome: (1) cell proportions; (2) the relative proportions between the lateral chapels' openings and the skeleton between them; (3) the rooms that fill space between lateral chapels. Both the analysis and the subsequent shape rules implications are described below.

(1) cell proportions

In Book 7, Chapter IV, paragraph two, Alberti describes the principles for defining the proportion of cells in rectangular temples. The rule of the treatise grammar considered these proportions, where cell length (*Li*) is directly dependent of cell width (*Wi*): $Li = \alpha\, Wi\ ;\ \alpha \in \{1, 1\ 1/3, 1\ 1/2, 2\}$.

Sant'Andrea's *Li* dimension corresponds to 3*Wi*, resulting in a 3:1 proportion. Although this proportion does not comply with the descriptions in Book 7, it is foreseen in the proportions described by Alberti in Chapters V and VI of Book 9 - *Ornament on Private Buildings*: "…The method of defining the outline is best taken from those objects in which Nature offers herself to our inspection and admiration as we view and examine them. […] The very same numbers that cause sounds to have that *concinnitas*, pleasing to the ears, can also fill the eyes and mind with wondrous delight. From musicians therefore who have already examined such numbers thor-

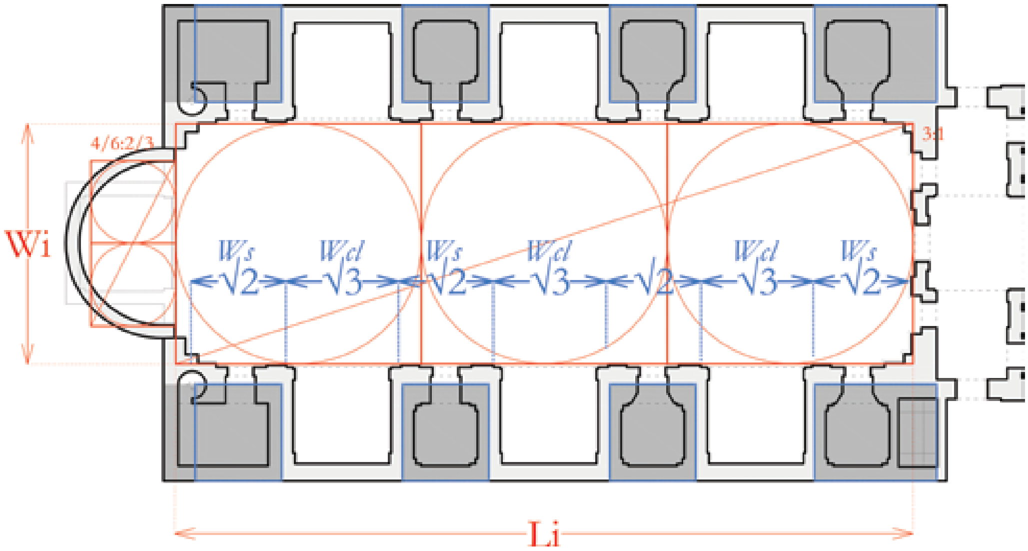

Figure 1
Sant'Andrea's plan summarizing the analysis of cell proportions; the skeleton between lateral chapels proportions; the rooms that fill space between chapels.

oughly, or from those objects in which Nature as displayed some evident and noble quality, the whole method of outlining is derived. […]"

On Chapter VI, Alberti refers to and describes in detail, the use of musical consonances to determine cell proportions. In synthesis, he defines that the proportions may be either short, long, or intermediate: as short proportions he considers *Square* (1:1), *Sesquialtera* (3:2) and *Sesquitertia* (4:3); as intermediate proportions *Double* (1:2), *Duplicate Sesquialtera* (9:4) and *Duplicate Sesquitertia* (16:9); and finally, as long proportions *Triple* (3:1), *Double Sesquitertia* (8:3) and *Quadruplus* (4:1).

In the same chapter, Alberti describes that *concinnitas* is reached by the use of musical consonances, but he also considers the use of *correspondentiae inatae to establish "*certain natural relationships that cannot be defined as numbers, but that may be obtained through roots and powers." Further reading of this chapter enabled the inference of correspondences between certain ratios – (√2:√1), (√3:√2), (√3:√1), (√4:√3) – that can be used to define proportions.

By incorporating the musical consonances in the initial conditions of *Rule 1*, the grammar will able to generate a temple with the length *Li* of Sant'Andrea (Figure 2 left), and with the further integration of the *correspondentiae inatae* in set of conditions, further solutions can be achieved by the application of *Rule 1*:

$Li = \alpha\, Wi\,;\ \alpha \in \{1,\ 1\ 1/3,\ 1\ 1/2,\ 2,\ 2\ 1/4,\ 1\ 7/9,\ 3,\ 2\ 2/3,\ 4,\ \sqrt{2}/\sqrt{1},\ \sqrt{3}/\sqrt{2},\ \sqrt{3}/\sqrt{1},\ \sqrt{4}/\sqrt{3}\}$.

(2) the proportion of the skeleton between lateral chapels

The proportional relation between lateral chapels openings (*Wcl*) and the walls separating the various chapels (*Ws*) is described on Chapter IV, Book 7, between paragraphs 4 and 7: "… the bones, that is, of the building, which separate the various openings to the tribunals in the temple - be nowhere less than a fifth of the gap, nowhere more than a third, or, where you want it particularly enclosed, no more than a half."

These parameters and conditions were synthesized in the *Rule 4* of the treatise grammar by the equation:

$Ws = \varphi' Wcl;\ \ 1/5 \le \varphi' \le 1/3 \lor \varphi' = 1/2$.

The *Ws* dimension is also dependent on cell

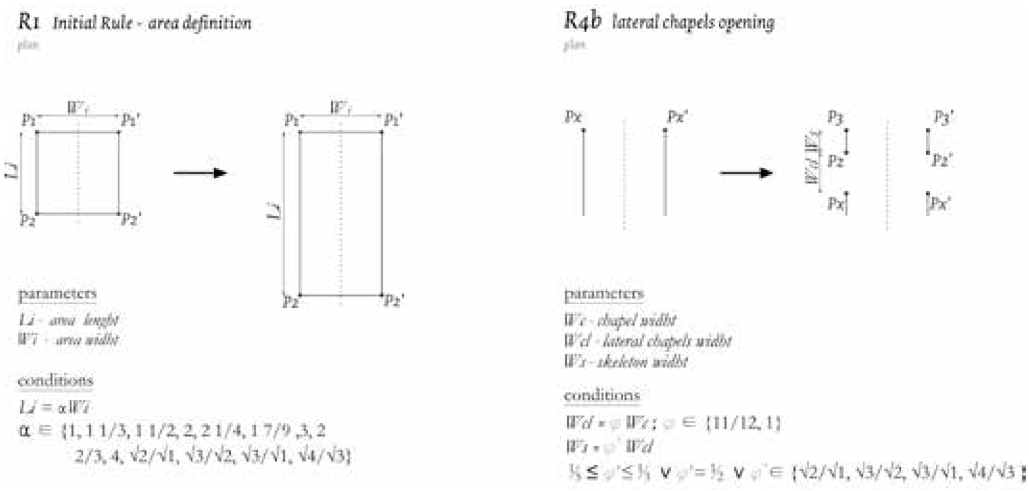

Figure 2
Shape rules from the rectangular temples grammar, with the included parameters and conditions: (left) Rule 1 defines cell proportions; (right) Rule 4b defines the lateral chapels' openings andplaces labels to design the chapel's outline using the set of Rules 5.

length *Li*, which is equal to the sum of the lateral openings, plus the width *W*s between them the temple's end walls, and it can be deduced by the following function:

$Ws = (Li - Ncl\ Wcl) / (Ncl + 1)$.

Since at Sant'Andrea, the proportion *Wcl*:*Ws* corresponds to √3:√2 (Table 1), it does not verify the conditions specified for φ' in the initial rule. In a strict understanding of the principles laid out in Book VII, such a non-correspondence could have been considered as an error in the Albertian canon. However, several authors (Tavernor, 1985; Kruger, 2011) showed that the use of the proportion √3:√2 to design the chapels' openings and the skeleton could be considered Albertian by introducing the use of *correspondentiae inatae* in the definition of such a proportion. The subsequently inclusion of such correspondences in the set of conditions in the original *Rule 4* (Figure 2 right) results in:

$Ws = \varphi'\ Wcl$; $1/5 \leq \varphi' \leq 1/3 \vee \varphi' \in \{\sqrt{2}/\sqrt{1}, \sqrt{3}/\sqrt{2}, \sqrt{3}/\sqrt{1}, \sqrt{4}/\sqrt{3}\}$.

(3) rooms filling space between chapels, frontispiece and rear facade.

In Sant'Andrea, the spaces in between the row of lateral chapels and the edges of the frontispiece and rear facade form a room connected to the cell thatconforms a rectangular plan (Figure 1). This spatial relation was not considered in the treatise shape grammar because it is not described in *De Re Aedificatoria*. While the addition of one single chapel per facade, as it happens in San Sebastiano, results in a relatively evident spatial relation between lateral chapels and the cell's wall, when several chapels are added to the same facade, such a spatial relation can be configured in several ways. The set of *Rules 7* (Figure 3 center) show the spatial relations translated from the treatise, while *Rule 7a'* and *Rule 7b'* (Figure 3 right) show the new spatial relations introduced by reproducing the ones existent in Sant'Andrea.

Sant'Andrea grammar add-ons

According to Terry Knight (1983), to transform a shape grammar, at least one rule addition, rule deletion or rule change has to be performed. By taking into consideration her definition of rule change: "Rule change changes a rule, initial shape, or final state by changing any of its spatial or nonspatial components: spatial relations, spatial labels, or state labels." - the operations performed to *Rule 1* and *Rule 4* can be considered a rule change because they add new dimensional conditions to the initial ones.

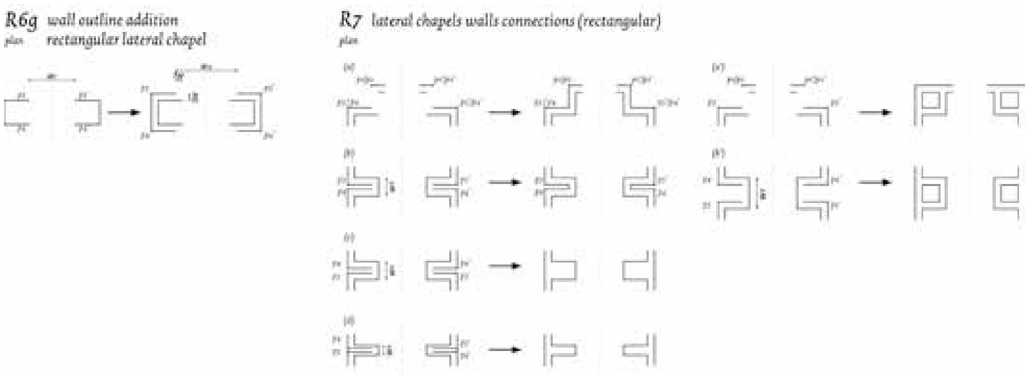

Figure 3
Shape rules that define the addition and arrangement of walls in lateral rectangular chapels. The left rules represent the rules added to the set of Rules 7, in accordance with the spatial relation inferred from Sant'Andrea.

Despite the maintenance of the parametric schema, new spatial relations can be achieved by resizing the plan. The addition of a new rule, as in the operation described above for the addition of *Rule 7a'* and *Rule 7b'*, can also be considered a transformation of grammar.

SHAPE GRAMMAR TRANSFORMATION WITH A CONSTANT RECURSIVE STRUCTURE

The treatise grammar followed mimetically the order of description of the temples' parts in the treatise. Their morphology is mainly described on Chapters IV and V of Book 7, in which the constituent parts of the temples are treated: cell – inner space of the temple, defined by the geometry of their area; tribune; lateral chapels and their skeletons; portico informed by the column systems – shaft, base, capital and entablature – and their proportions; pediment; walls; roof; and main openings.

While in Palladian Villas grammar (Stiny, 1978) the Villas constant partition features were useful to define the grammar recursive structure, in Alberti's built work, the few examples of designs of sacred buildings, and the typological variety of those examples do not seem to be the more appropriate for setting up a grammar representative of Alberti's sacred buildings. From the reading of the treatise, it was possible to consider a framework for the definition of the morphological parts of the temples and their interrelations, which have been applied to define the recursive structure of the treatise grammar. Since this structure encapsulates the formal and parametric logic of Alberti's buildings, it was decided to maintain the core of their recursive structure during the transformation process. Although the recursive structure of the grammar was kept, several rules were transformed by changing their spatial relations, and other rules were added.

Figure 4 shows a step by step computation, illustrating the different options of derivation at each step, where only one derivation is subsequently transformed by the use of the next set of shape rules.

THE CLASSIC NUMBER VERSUS THE CONTEMPORARY PARAMETRIC MODEL

The 'number' in the algorithmic nature of De re aedificatoria translated by contemporary eyes

In classical philosophy, numbers have a specific meaning before its scientific dimension. Alberti systematizes classic architectonic dimensions through considerations on the perfection of numbers, as well as establishing relationships between music harmonies and proportional systems in architecture (Book 9, V).

In Nexus 2002 conference, during a round table discussion about the significance of both the quan-

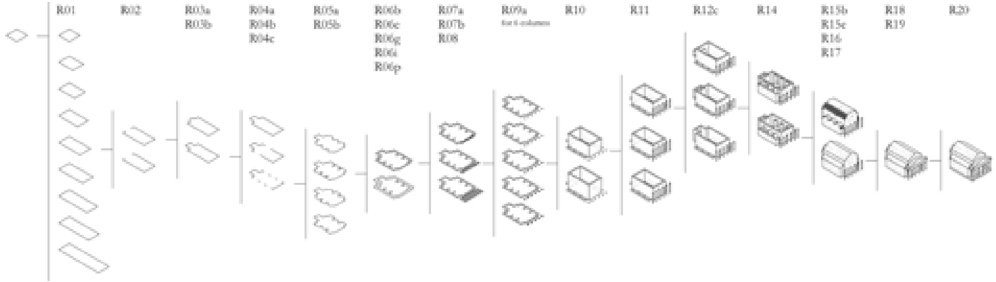

Figure 4
Computation tree of the temples shape grammar showing only one possible subsequent rule application at each step of the computation.

tity and the quality of numbers in *De re aedificatoria*, Lionel March in answering to Robert Tavernor's question [2] - "Can anyone explain exactly what might be meant by the "quality" of a number?" - argued for the numbers dual nature in the treatise: "When Alberti was writing, the words 'quantity' and 'quality' still retained their Aristotelian roots. (…) Thus, from an Aristotelian perspective, in giving shape to an architectural work, Alberti is engaged in qualitative decisions, but in dimensioning the work he is acting quantitatively. (…) A pediment is qualitatively 'triangular', but its dimensions are quantitatively 24 feet long to 5 feet high."

March's argument in the discussion of number significance follows to the idea that "a contemporary approach would be computational with respect to 'number' and semiotic with respect to reference and usage.

The treatise grammar inference and their subsequent transformation followed this notion of working simultaneously with a 'contemporary' understanding of 'shapes' and 'numbers'. 'Shapes'configure the essence of the spatial relations of shape rules, while 'numbers' introduce their dynamic dimensional significance.

De re aedificatoria a pre-digital parametric model

The process of inferring shape rules directly from the reading of *De re aedificatoria* exposed the algorithmic nature of their content. Alberti notations on the sacred buildings parts are described in terms of numerical qualities and quantities defining their proportional and morphological dependency. Thus, the schema presented in Figure 1 and the shape rules illustrated in Figure 2 feature the possibility of assigning different values to their dimensional parameters and also by the interdependencies between the cell and chapels dimensions and location, resulting in a parametric shape rule. This kind of relations is repeated in other shape rules resulting in a parametric grammar (Stiny, 1980).

Like the initial grammar, the transformed grammar still is a parametric grammar. Therefore, each derivation of the grammar can potentially generate a family of design solutions, rather than one single solution. A computational parametric model was developed in Grasshopper with the aim of managing the generation of multiple design solutions within the grammar (Grasshopper is a Visual Programming Interface that interacts with modeling software Rhinoceros. A program written in Grasshopper consists of a combination of interlinked components performing operations on primitives, usually but not necessarily geometrical ones. This programming paradigm allows visually developing parametric geometrical models, whose outputs correspond to a family of solutions). The parametric model encodes the knowledge gathered in the grammar inferring and transformation processes. The output depends on the variation of parameters, which correspond to what Alberti prescribes for the number and dimensions of the elements that should, according to the author's theory and practice, conform the temple (Figure 5).

In the last three decades, computational tools

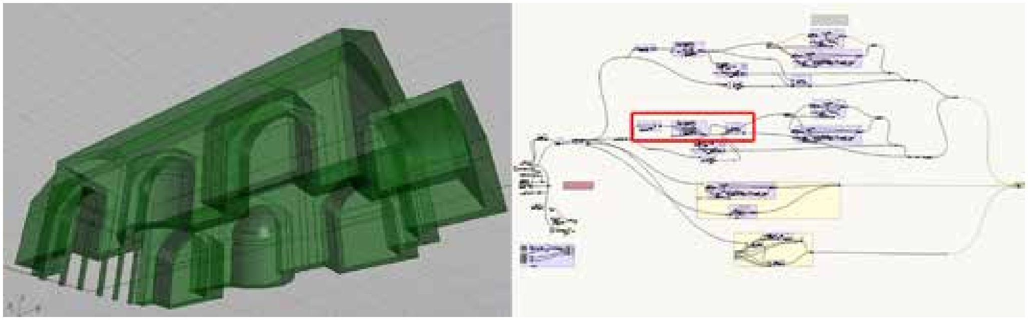

Figure 5
Parametric model and one possible design solution99.

gained an extraordinary importance in the contemporary architectural discourse. Parametric design is one of the computational models that acquired more relevance in these process. Despite their importance, little discussion has been given to the use of parametric design in a pre-digital era. The translation of Alberti's work into a shape grammar revealed that the *De re aedificatoria*'s descriptions of sacred buildings is precursor to the use of parametric design to define a set of architectonic principles. Thus, it is inevitable that a research on *De re aedificatoria* today gives rise to its implementation as a computational model.

CONCLUSION

The variety of context and the role that Aberti had in the design of his buildings results in very specific knowledge that can be retrieved from them. Thus, the sole analysis of the buildings were not sufficient to set up rules defining a consistent architectural typology. Furthermore, they do not always verify his treatise's principles. Regarding to this subject, Tavernor (1996, p. 178) remembers that Alberti (IX, 10, p.137) made reference to the difficulty of translating his theoretical principles in a successful design: "I can say this of myself: I have often conceived of projects in the mind that seemed quite commendable at the time; but when I translated them into drawings, I found several errors in the very part that delight me most, and quite serious ones; again, when I return to drawings, and measure the dimensions, I recognize and lament my carelessness; finally when I pass from the drawings to the model, I sometimes notice further mistakes in the individual parts, even over the numbers"

Despite this incongruity, the analysis of the buildings contributed for the systematization of a coherent body knowledge of Albertian sacred buildings because our focus on the buildings was constrained by our concern for the structure of the treatise grammar.

The methodology presented for the inference of transformations of the treatise shape grammar contributed for encoding new knowledge into the grammar. Although, the algorithmic nature of the treatise descriptions eased the task of matching building proportions and morphology with the grammar shape rules, this reinforces the notion that inferring rules from the analysis of a corpus of existing buildings is an adequate tool to reinforce a grammar's capability for generating solutions in accordance to both textual and design descriptions (Mitchell, 1990).

Both shape grammar and parametric model implementations prove to be effective tools for generating design solutions in the same style. The former introduces a step by step computation that reinforces the visual perception of formal transformations. The latter, by automating the process of generation, emphasizes the variation on the solutions by controlling their parameters. Even though their structure has different philosophies, they used the same knowledge on the design, resulting in the same corpus of solutions.

Given the objectives of the project Digital Alberti, it is supposed to expand the methodology presented to a set of sacred buildings, representative of classical Portuguese architecture. The aim of this analysis is to identify possible deviations and similitude between Alberti theoretical and design principles and classical Portuguese architecture. The results of these investigations it will be presented in future essays.

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A Parametric Recreation of Traditional Chinese Architecture

A case study on the floor plan

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Abstract. *This paper presents the current state of progress investigating the possibility of modelling traditional Chinese architecture using parametrics based on the two rule books. This builds on the work of producing systematic analysis on both rule books and contributing knowledge from extant buildings. The case study target is the floor plan described in Ying Zao Fa Shi. Discussion and future works are suggested at the end.*
Keywords. *Parametric modelling, traditional Chinese architecture, Ying Zao Fa Shi, Kung-ch'eng tso-fa tse-le, floor plan.*

INTRODUCTION

When studying traditional Chinese architecture, two references are essential—literary records and extant buildings. China, a country with over 5000 years of history boasts remarkable architecture from all dynasties and periods. Unfortunately, almost none of the buildings before Tang Dynasty (618-907) remain and many buildings from Song Dynasty (960-1279) to Ching Dynasty (1616-1912) have been badly damaged or destroyed.

However, two important texts survive: *Ying Zao Fa Shi* (Building Standards) from Song Dynasty and Ching Dynasty: *Kung-ch'eng tso-fa tse-le* (Structural Regulations) from Ching Dynasty, which are known as the "two text books of Chinese ancient architecture" (Liang, 1985). They are the only remaining classical Chinese literature which deals with architecture and are, in essence, rule books that govern most aspects of the design. As a starting point, the analysis on the two rule books is a key factor in understanding architecture of this period. This paper looks at generation of the floor plan using the *Ying Zao Fa Shi*. A series of rules and hypotheses are reviewed before the generation of the floor plan models using Grasshopper and Rhino. The models are discussed and evaluated and additionally, the comparison with parallel research of the Shape Grammar approach to the floor plan is discussed.

THE TWO RULE BOOKS

Figure1 illustrates the chronological diagram indicating a brief history of China and the two dynasties (in the square boxes) in which the two rule books were compiled.

Ying Zao Fa Shi (Li, 1103) was the official building standard as a guidance of design and construction in Song Dynasty. During the period of the Song Dynasty, an increasing number of different levels and types of buildings were constructed which led to an urgent requirement of an official instruction. There were three original purposes of this book. First, to set the design guidelines to articulate the social status of feudalism. Second, to establish a unified architectural form and style to guarantee a consistent level of detail and artistic effects. Third, to define

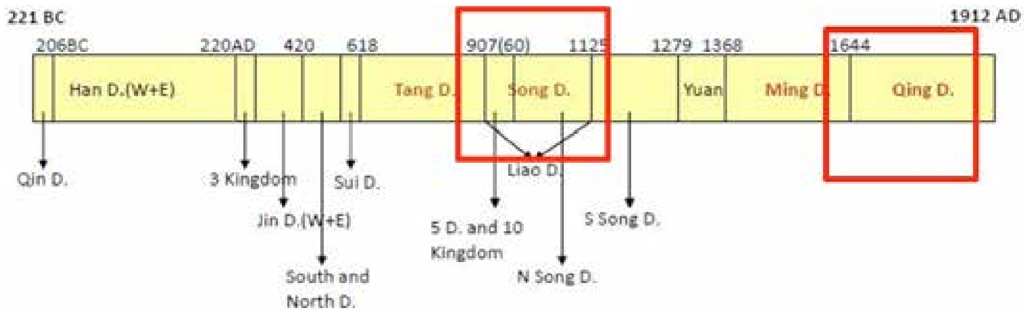


Figure 1
Chinese dynasties in chrono-logic order.

the material choices and quantities as well as the work load to avoid corruption and embezzlement. The first edition was published in 1091 and with extended second edition compiled by Li Jie, the court architect of the Hui Zong Emperor in 1103.

This book consists of thirty-four volumes. Volumes one and two are the overall introduction to different types and components of the architecture. Volume three is about the foundations, masonry structures and carving of handrails. Volumes four and five introduce the structural carpentry system. Volumes six to eleven introduce the finished carpentry. Volume twelve includes three timber precast methods and bamboo weave method. Volume thirteen explains tile and cement processing. Volume fourteen focuses on the composition and colour matching of decorative painting. Volume fifteen describes the precast of bricks and ceramic materials. Volumes sixteen to twenty-five presents the work load required in the previous volumes. Volumes twenty-six to twenty-eight outlines the material consumption of the components mentioned above. Volumes twenty-nine to thirty-four are the selected diagrams.

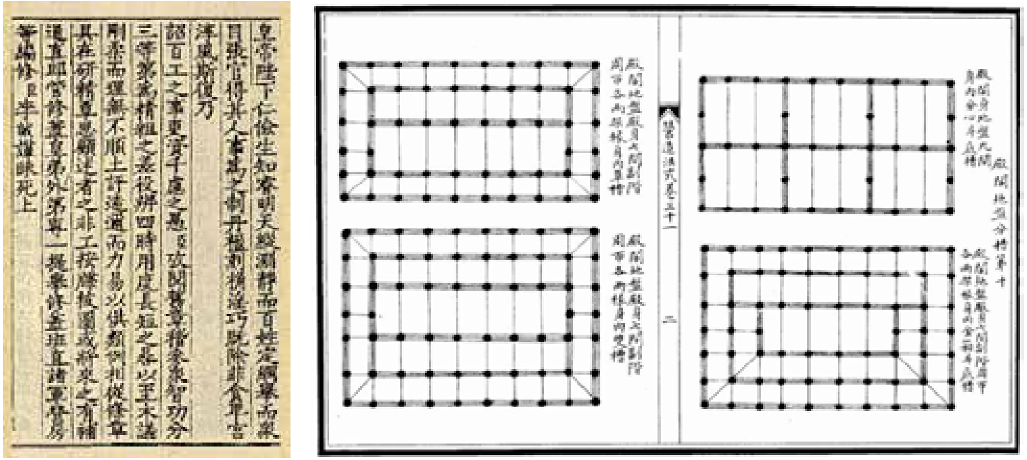
The significance of Ying Zao Fa Shi is not "simply for its existing" (Li, 2001). The book is, in general, well organised, logical, systematic and rigorous which is quite rare in ancient literature. Although some aspects such as the floor plan are relatively lacking in systematic description, the whole book provides readers with a "rule-based and parametric" system (Li, 2001) for the ancient style buildings. Liang (1983) even points out that the Hui Zong Emperor was a naive politician, but was an excellent artist. Meanwhile Li Jie was also good at drawing and music. This might be one reason why occasionally Li Jie omitted some important descriptive rules but paid more attention to the architectural style and decoration. Together with Li's research (Li, 2001; 2003) and the on-going research in the case study on the ting tang section by the authors, it has been shown that Chinese traditional architecture has some parametric characteristics.

As shown in Figure 2, Ying Zao Fa Shi was written in an ancient form of the Chinese language which has no punctuation. The characters, vocabulary, grammar and text direction were all different from contemporary written Chinese which presents a big problem to modern researchers. In relative terms, Ching Dynasty: Kung-ch'eng tso-fa tse-le (1734) is linguistically more acceptable since it is compiled in 1734, more than six hundred years closer to us. Meanwhile, more extant buildings from Ching Dynasty can be studied as practical evidence. In this book, twenty-seven types of buildings with accurate size and dimensions are given as examples, making it useful for reconstruction of buildings of the period.

RULES FOR THE FLOOR PLAN AND PARAMETRIC APPROACH

In order to understand and recreate floor plans, a description of the ancient floor plan system is necessary. In Ying Zao Fa Shi, the following factors or pa-

Figure 2
Sample pages of Ying Zao Fa Shi (left: text description [1]; right: floor plan diagram [2]).

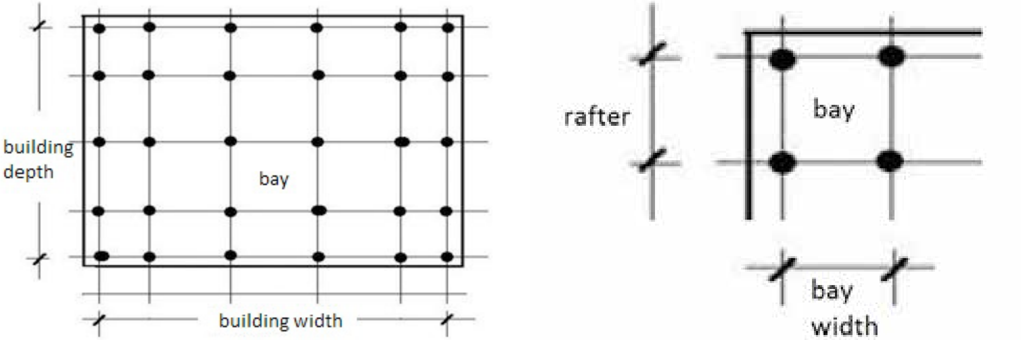


rameters can be used to describe a building:

- The building type (such as dian tang or ting tang, here tang means hall).
- The overall dimension (measured in modular unit):
- Building width (and bay width)
- Building depth (and rafters)
- The grade (which is used to calculate the absolute value of the modular unit)

In the most common and formal cases, the floor plan of a single house is rectangular and consists of two major factors: building width and building depth, which determines the dimension and scale of the house. The building width and building depth form the area of a building. This area can be divided into small units (small rectangles) ie bays (usually, each bay has four columns at the four corners, although not in every case). Each bay is determined by the bay width and bay depth, as shown in Figure 3. The sum of the bay width or bay depth gives the building width or depth. But in reality, the bay depth is not described in the set of parameters above. Instead, the horizontally projected rafter is used to measure the depth. There are three reasons. First, Ying Zao Fa Shi mentions for ting tang type building, one bay depth equals to two rafters deep but it does not mention the relationship for the dian tang type building. Therefore in order to unify the parameters

Figure 3
Factors of the floor plan.



Size of fen (in cun)	0.60	0.55	0.50	0.48	0.44	0.40	0.35	0.30
Grades of dian tang	1	2	3	4	5			
Grades of ting tang			3	4	5	6		
Grades of other types						6	7	8

Table 1
Absolute values of fen for different grades.

	ting tang	*dian tang*
Building width (number of bays)	3,5,7,9 bays	3,5,7,9,11 bays
Building depth (number of rafters)	4,6,8,10 rafters	2,4,6,8,10,12 rafters
Bay width	200-450 fen	
rafter	≤ 150 fen	

Table 2
Definition of the four parameters.

in the later parametric modelling, the rafter is selected as the depth measurement for both building types. Second, to be consistent with the research of case study on the section, the rafter is a key parameter in defining the section. The rafter is closely related to the disposition of the columns and beams and the total number of columns. Third, from the workers' experiences, they tend to use rafters rather than bay depth. Apart from the rectangular forms, there are also several non-rectangular floor plans, known as non-formal architecture, which includes the use of the triangle, circle, sector, octagon, polygon, and the superposition of polygons and Wan shape. They are widely used in pavilions and gardens which typically appear in Southern China. But these irregular shape floor plans are not discussed in this paper.

At this point, it is worth describing the measurement units used. Depending on the eight grades of the buildings, a fen can have eight different absolute values (Liang, 1983), measured in cun (a Chinese length unit), as shown in Table 1. Given that 1 cun = 32mm approximately in Song Dynasty, the final absolute values of width and depth can be obtained. For example, if the building is ting tang type and in Grade Three, 1 fen =0.5 cun x 32mm/cun=16mm.

In order to build up the parametric logic, there are four more details which need to be clarified: the value of bay width and rafter, and number of both (which constitutes the building width and building depth). Unfortunately, at this stage, Ying Zao Fa Shi does not provide a systematic definition. Instead, it gives information partially by defining and partially by enumerating. Despite this, the parametric model could still be built up by first making hypothesis based on the information in hand and then evaluating with the diagrams in the rule book and extant building measurement data. The assumptions here are based on the investigation of historian Chen (1993). As shown in Table 2, the four parameters are summaried. In particular, the bay width is not given directly. The calculation is as follows: a bay has two sets of dou gong (the bracket joint) that sit on each side of the columns (the black dots in Figure 3) and either one or two sets between the columns (intercolumnar dou gong). The centre-to-centre distance of dou gong is 125 fen ± 25 fen. Thus the bay width with one intercolumnar dou gong is 250 fen ± 50 fen, and with two intercolumnar dou gong is 375 fen ± 75 fen. Therefore the total range of bay width is 200-450 fen. In addition, the centre bay is often wider and in most extant examples the two outer bays are often slightly narrower than the others [3]. In the table, the modular unit fen is used rather than the absolute values.

After all the parameters are clarified, the parametric model now can be built. Figure 4 shows the logic diagram for the parametric modelling. In this logic diagram, ting tang and dian tang types are integrated together since Liu (1984) points out that "although Ying Zao Fa Shi distinct the two types strictly, buildings are slickly dealt with in practice". The rectangular floor plan grid is set first by defining the x-y plane as the base plane. The next step is to define the size and number of bays. In order to achieve this, the four parameters described above are outlined here. As the primary parameters, the

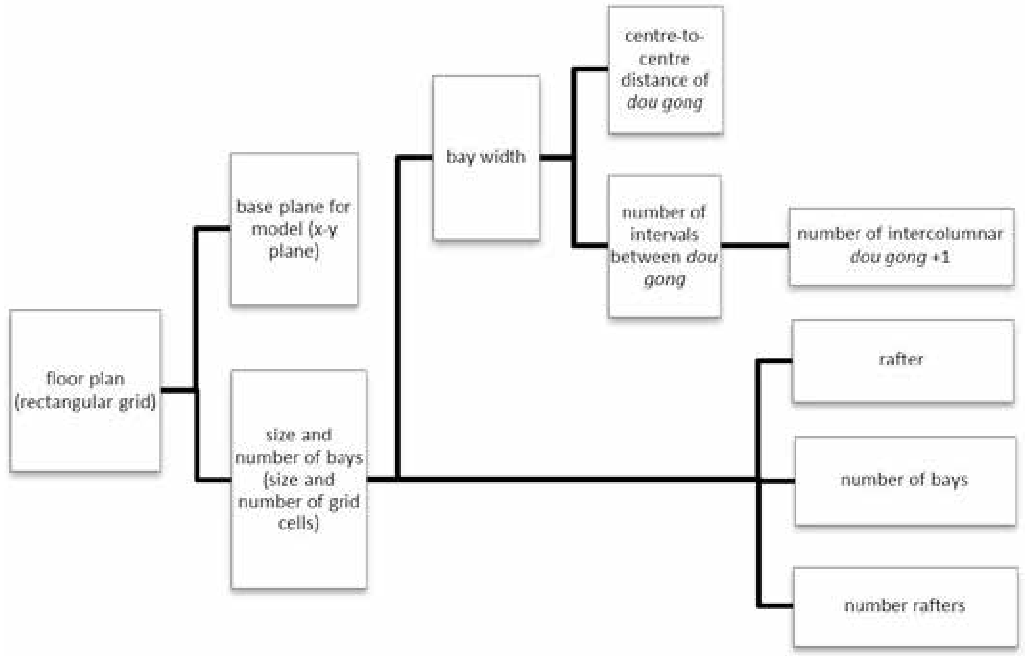


Figure 4
Parametric logic diagram.

rafter, number of bays and number of rafters can be directly controlled by the corresponding number range listed in Table 2. The bay width is a multiplication of two factors: centre-to-centre distance of dou gong and number of intervals between dou gong. Additionally, the number of intervals between dou gong is equal to the number of intercolumnar dou gong plus one. Since the number of intercolumnar dou gong is known directly, this is the fourth parameter. Thus, overall, there are only four simple parameters that can be controlled depending on the building type and grade. In addition, there is one judgment in this logic diagram: the building width should always be larger than the building depth. And if so, the conclusion will appear true. Under this one set of logic diagrams the floor plan of both ting tang and dian tang types, all eight grades of building with different bays and rafters are involved. Figure 5 shows two examples of the model.

Comparing the examples with the diagrams in Ying Zao Fa Shi (Figure 2 right), they are highly consistent in form. And there is one extant building example—Fuoguang Temple Wenshu Dian (Figure 6), which built at 1137, located at Shanxi Province. It is a Grade Two dian tang type building with seven bays. From the parametric model, the minimum building width is given as 7x200x0.55x32=24640mm=24.64m while the maximum is 7x450x0.55x32=55440mm=55.44m. Similarly, the building depth spans from 15.84m to 21.12m. Wang (2011) provides its measurement data of 31.56m in width and 17.60m in depth. As Liu (1984) argues that "there is not such an extant building completed follows Ying Zao Fa Shi found so far", if the measurement data is within the range of the parametric model, then the two are consistent.

DISCUSSION

Parametric design differs from the conventional design mode of adding and removing marks in that

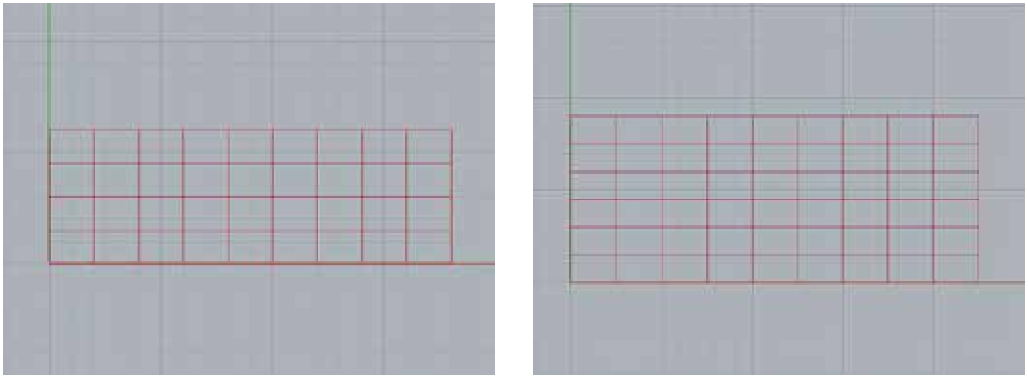


Figure 5
Examples (left: 9 bays 4 rafters floor plan; right: 9 bays 6 rafters floor plan).

the relationships between the parameters are the essence of parametrics. In this case study, the relationships are not based on one specific example, but a systematic description and summary of all the buildings in a typical period—which are the rules. The logic diagram of the formal rectangular floor plan is then built up based on the rules. Following this, different outcomes can be generated to indicate the advantages of parametric method which can result in different final products without a new set of logic diagrams or the removal/addition individual components. In particular, all the floor plan formats are included in this set of logic diagram, including both the building types (dian tang and ting tang), any dimensions and all the grades.

There is parallel research in the Shape Grammar approach to the floor plan (Li, 2001). In the research, Li derives the process with initial symbols and a set of rules, and then the design rules act on the initial symbols repeatedly, resulting in a final design. Following each typical set of rules will result in one corresponding final design. Thus Shape Grammar generates a language of design. How and in what sequence do the rules applied makes up the so called grammar? Compared with Li's research (Li, 2001), the advantage of the parametric method is the ease with which the process can be extended into three dimensional modelling. For instance, the intersectant points could be the column locations when combining with the case study on the section. Then, the two dimensional representation of architecture through the plan and section will form the three dimensional parametric model. And indeed, according to Wang (2011), more special proportions (relationships) exist in the elevations, as well as many other building factors. On the other hand,

Figure 6
Fuoguang Temple Wenshu Dian [4] [5].

if all the attempts are limited in two dimensional planes, it may omit rules and relationships that exist between the section and the floor plan.

CONCLUSION

Accordingly, three major similarities between Shape Grammar and parametrics can be drawn. Both of them are derived systematically and logically; both of them are generative and productive; both of them can be symbolically and graphically illustrated. In contrast, three key differences can be identified as well. The parameters in parametric method can be any variables, abstract or concrete, without the limitation of just geometrical entities. The rules used in parametrics can be any logic relationships, not only repetitions and the final outcome could involve many different variations.

When combined with parallel work in the parametric generation of the ting tang section, it is found that the characters summarized from deriving the floor plans are consistent with those from generating sections. Taking Li's work (Li, 2001) of shape grammar approach to the floor plan and ting tang section into consideration, it can be concluded that Chinese traditional architecture has parametric characteristics. Since the whole structure of traditional buildings constructed using the rule books is complex and closely interrelated, a parametric method has the advantage of illustrating and generating the principles from the rule books to complex digital reconstructions. The application is not limited to the restoration of ancient building, but could also be used as inspiration in the generation of new designs. Apart from individual buildings, based on the floor plan logic diagram, a similar parametric method can be used in recreation of many city plans, since several Chinese ancient cityies also show parametric characteristics.

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A Bottom-Up Social Housing System Described with Shape Grammars

The case of Belapur low-income housing development

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Abstract. *This paper presents the analysis of a bottom-up design system using shape grammars. This research is part of a larger study that proposes the development of a generic grammar to improve the quality of site development in social housing plans, including the improvement of their public spaces. We show the use of shape grammars as an analytical method to study the design of Belapur social housing development, designed by Charles Correa, in 1983.*
Keywords. *Design methodology; shape grammar; analytical grammar; low-income housing.*

INTRODUCTION

This research aims at applying shape grammars as a method for generating improved social housing design systems which may contribute to the development of more diversity in external areas and public spaces, creating identity and appropriation by its dwellers. In order to achieve such goals we start by analyzing social housing plans as case studies to infer design patterns to propose the development of generic grammars, which may enable the generation and management of incremental housing systems with locally captured spatial qualities. In the book A Pattern Language (1977), Alexander and his collaborators define a theory and application instructions for the use of a pattern language at different design scales - from the scale of the city and urban design to the building scale, garden and layout of housing units. The main goal of this research is to define a methodology for developing bottom-up housing systems able to be implemented as incremental urban developments based on the progressive addition of housing clusters and associated community areas. The underlying hypothesis is that we can develop a set of generic parallel grammars which allow (and control) the generation of such housing systems.

OBJECTIVES

This paper is part of a larger study that proposes a development of a generic grammar to improve the quality of low-income housing plans, including the improvement of public spaces and community areas. The generic grammar is developed from analysis of four case studies by capturing the underlying common rules that were used in their design. The four case studies are: Belapur plan – located in New Bombay, India, designed by Charles Correa in 1986, Jardim São Francisco, – located in São Paulo, Brazil, designed by Demetre Anastassakis in 1989, Proyecto Experimental de Vivienda (PREVI) located in Lima, Peru, designed by Christopher Alexander in 1969 and Quinta Monroy, in Iquique – Chile, designed by Elemental in 2004. This paper is focused on the analysis and grammar development of the Belapur plan.

The structure for developing a generic grammar consists of 4 parts: (1) the inference of a specific analytical grammar from an existing case study; (2) creating a generic grammar by generalizing the grammars obtained from the analysis of the case studies; (3) to improve the quality of the final designs the generic grammar is revised according to qualitative requirements for public and community areas based on urban design and housing plan literature (Pedro, 1999; Barton et al., 2010); and (4) applying the new revised grammar in the development of specific designs for social housing plans. Pedro (1999) developed a systematic methodology of qualitative requirements to be applied in the development of housing complexes in Portugal and Barton *et al* (2010) presents a set of guidelines to design neighborhoods that are safe, friendly and attractive. This literature contributes to define the qualitative requirements to be applied as a control mechanism in the generic grammar. The generic grammar is organized in small thematic generative sets corresponding to design patterns following the principles defined in (Beirão et al., 2012).

DESIGN METHODOLOGY

The design methodology consists on the use of shape grammar as an analytical method applied to study the design of Correa's Belapur plan, to capture the design method used by the architect to obtain emergent community areas as the result of the recursive application of local rules involving spatial relations between plots and common public access areas. The interesting aspect of the Belapur plan is that it succeeds in generating simultaneously housing types and an emergent hierarchized structure of public space. The spatial relations and local rules can be expressed in the form of a shape grammar describing the Belapur housing system as an incremental system following Correa's cardinal principles of incrementality and malleability as defined in his bill of rights for housing in the third world (Correa, 1999).

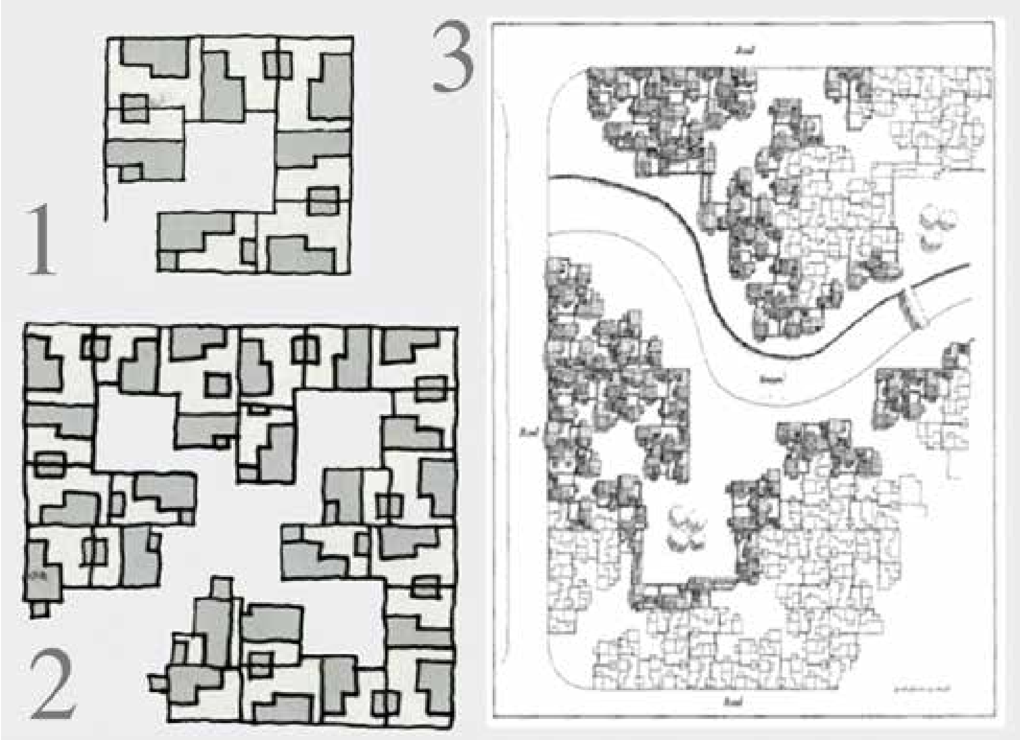
From the analysis of the case studies it is proposed to infer a set of generic design patterns codified as shape grammars. The concept of generic grammar was presented by Li (2001) and consists of a widely applicable shape grammar embedding the features of a reasonably abstract language which is able to produce design in several specific languages by adjusting the grammar accordingly. Current researches present the application of generic grammars in different contexts - Benrós et al. (2012) proposed developing a generic grammar applied to housing and Beirão (2012) developed a generic grammar for urban design context. However the novelty of the ongoing research lies in the use of this approach in a different scale – between housing scale and urban design scale, and to present a bottom-up design system for the development of a housing complex which includes emergent public spaces related with the traditional use of public space. The generic grammar obtained by such analysis will then be assessed by comparing its features with the quality requirements defined by (Pedro, 1999; Steiner and Butler 2007; Barton et al., 2010). The goal is to obtain an improved grammar containing heuristics based on the above mentioned quality requirements. Such structure resembles that of a discursive grammar as defined by Duarte (2001).

This research is seen as an initial step in the development of a generic grammar for social housing developments, especially regarding the generation of housing plans, public spaces and community areas. It goal is to add to the typical mass production strategy, features of diversity both at housing level and public space level.

CASE STUDY: BELAPUR – CHARLES CORREA

The Belapur Housing was designed by Charles Correa, in 1983-1986 to accommodate more than 90%

Figure 1
1. Belapur housing development: 1.7 housing units around a courtyard 8m x 8m; 2. bigger module of 21 houses, surrounding a community space of 12m x 12m; 3. Sitting plan (Correa, 1989).



of Bombay's low-income profile with a variation from 45m2 to 70m2 on house typology. The project demonstrates high densities – 500 inhabitants per hectare, including external areas, schools, etc (Correa, 1999). The site is located on six hectares of land 1 km away from the city center of New Bombay and the development had to cover almost the entire range of low-income groups – from the lowest to the upper-middle categories (Correa, 1989). This plan presents a hierarchy of community spaces as a fractal structure; it consists of organizing 7 housing units around an intimate courtyard with approximately 8m x 8m (Figure 1-1). This composition is repeated at a higher scale as shown in Figure 1-3 creating a similar composition which can itself be repeated at an even higher scale, hence creating the fractal structure. The first configuration provides more privacy and a sense of neighborhood at the smaller scale. Three of these clusters combine to form a bigger module of 21 houses, surrounding a community space of 12m x 12m (Figure 1-2).

The houses were designed as an evolutionary module, where "units are packed close enough to provide the advantages of high density, yet separate enough to allow for individual identity and growth" – this strategy allows growth from "a single lean-to roof to urban town-houses" (Correa, 1989; 1999) because each dwelling is freestanding and does not share any wall or land with its neighbors, allowing a family to extend its home according to their needs by means of self-construction. Such policy towards house extension resembles that of the Elemental concept developed by Alejandro Aravena (Aravena and Iacobelli 2010). The plan clearly expresses Correa's principle of incrementality and order becomes an underlying feature which emerges in the growth process.

BELAPUR HOUSING SHAPE GRAMMAR

The Belapur plan was analyzed because this design concept contains qualities that allow growth at a local level through a bottom-up process and contains rules to evolve and generate hierarchical external spaces and community areas. This shape grammar gives rise to a growth system as a fractal structure. In other words, this *bottom-up* approach is capable of responding to growth needs and provide social and community spaces according to populations' needs. According to Correa:

"If there ever is a Bill of Rights for housing in Third World, it would surely have to include – enshrine! – the following cardinal principles: Incrementality, Pluralism, Malleability, Participation, Income generation, Equity, Open-to-sky space, Disaggregation" (Correa, 1999, p.109).

The bottom-up reasoning underlying the design can be demonstrated in the shape grammar that we developed. The system can be described with three parallel grammars: Grammar A, which fills lots with an initial house volume, Grammar 0 which defines the house extension rules within the lots and Grammar B which defines spatial relations between blocks.

In this paper we focused our attention on the emergence of public space order, in particular, in the emergence of the three hierarchical levels of public space. To do so, and due to space constraints some assumptions were considered to simplify the presentation of the argument in discussion here. Furthermore, Correa's drawings actually show less than the real potential underlying his system, even though his claims for incrementality and malleability would suggest a much wider use of the rules and the exploration of other simple variations as it will be argued in the discussion section. As such, the assumptions considered here are basically two. First, that the block - 7 lots organized around a common public space - is always the same, i.e., has exactly the same geometry and is always composed of identical lots although slightly different within each block. This corresponds exactly to Correa's drawings (Figure 1). Second, Grammar 0 is ignored here for it does not play any role in the emergence of public space. However, because some of the block rules (Grammar B) are related with the fact of a lot being already built or not we assume that the Grammar A simply fills a lot with a fixed house shape (Figure 3).

The combination of these grammars generates designs in an incremental way following Correa's cardinal principles by applying the mentioned grammars in parallel. The process is mainly additive and based on local rules which act according to vicinity conditions (Figure 2).

Grammar A

Grammar A consists of organizing 7 housing units by filling lots around an intimate courtyard. In its initial state each lot contains a label (+) defined as "RI 01", which can be replaced with a house. Placing the first house turns off all labels (+) except those in neighboring lots (Figure 3). This rule guarantees that the generation proceeds by following a neighboring condition. The block is filled by replacing labels + with houses and adding + labels to the empty neighbor lots until all lots become filled (see rules RL 01 to RL 07).

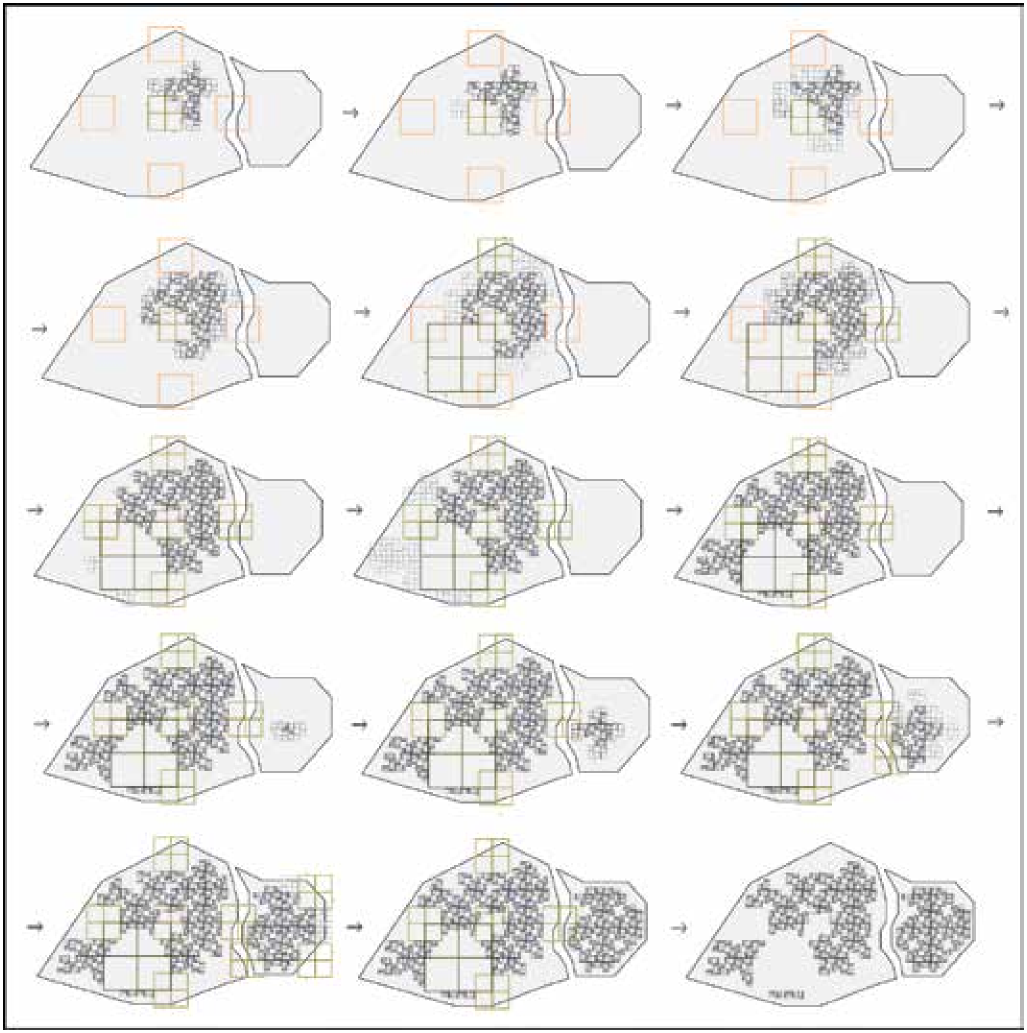
The first lot to be filled along a side of a block generates a label (▲) at the side of the block for applying the Grammar B, which may be applied in any iteration since the moment the label is available (Figure 4).

The rule RL 08 defines the insertion of the label (A) whose function is to remove one lot, thereby enabling the permeability of the block. This feature allows the grammar to create different access paths to the housing blocks as well as greater diversity of public spaces (Figure 5).

Grammar B

The set of rules generates urban scale design by defining spatial relations between three blocks (21 houses), around a community space. The Grammar B

Figure 2
Belapur shape grammar derivation.



consists in 4 rules by associating two blocks: all rules erase the label (▲) and associate a new block with 7 lots in 4 distinct spatial relations. The rule defined as "Start Block" (RS) replaces the new block in gray and starts the Grammar A placing labels (+) in the existing lots (Figure 6).

Control rules

Control rules deletes labels in the space of one block by inserting optional 4 lots with houses. Thus, the community area allows the insertion of 3 more areas which are constituted as a courtyard. The labels ● and ▲ defines possible association with other

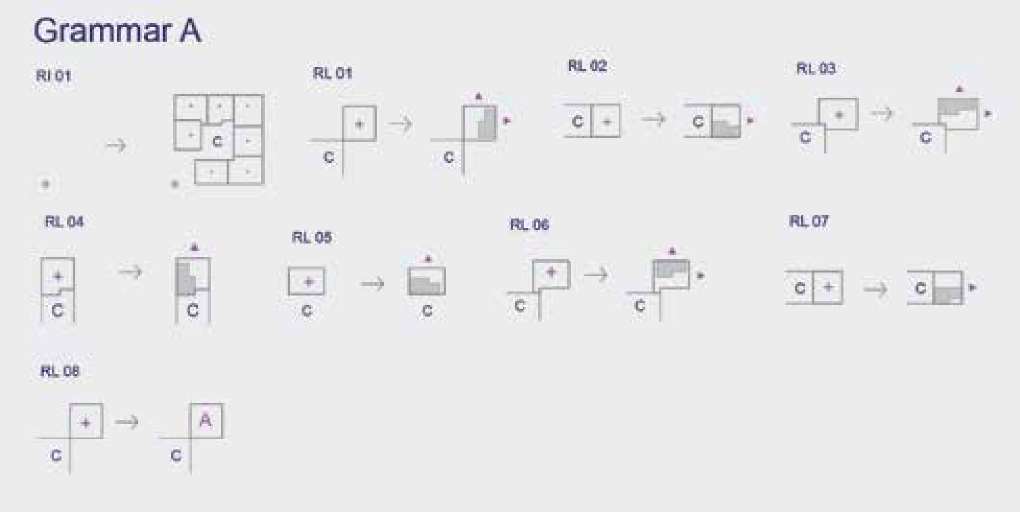


Figure 3
Grammar A.

blocks (Figure 7). Note that labels ● and ▲ concern two different spatial relations regarding the orientation of the blocks. The rule RC 09 removes one of the optional lots inside the courtyard (see Rule - RC 02) and inserts a portico to isolate a neighborhood unit constituted by three blocks. Thus, the rule allows creating different levels of privacy in accordance with the growth of the scale of public spaces.

After applying control rules that generate the common spaces of the housing development, it is possible to apply the rules of Grammar B (see rules RB 05 to RB 08) which allow the continuous insertion of blocks and increase the scale of public space (Figure 8).

The Grammar B' defines association between blocks with corner for the passage and association of the square and block: all rules off label (▲) and associate a new block with 7 lots in two distinct spatial relationships (Figure 9).

DISCUSSION

The paper presents the Belapur grammar as a design system, which may contribute to the future development of a generic grammar for social housing plans. The development of a generic grammar for housing intends to contribute to the improvement of public spaces and community areas by insertion **of** qualitative requirements as a control mechanism that allows adding public spaces and facilities in a hierarchical structure in accordance to needs.

The bottom-up grammar's structure explains the concept of incrementality, pluralism and malle-

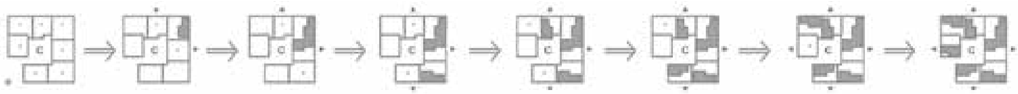


Figure 4
Derivation of a block.

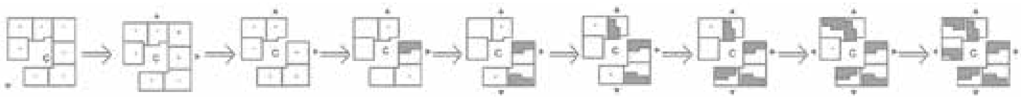
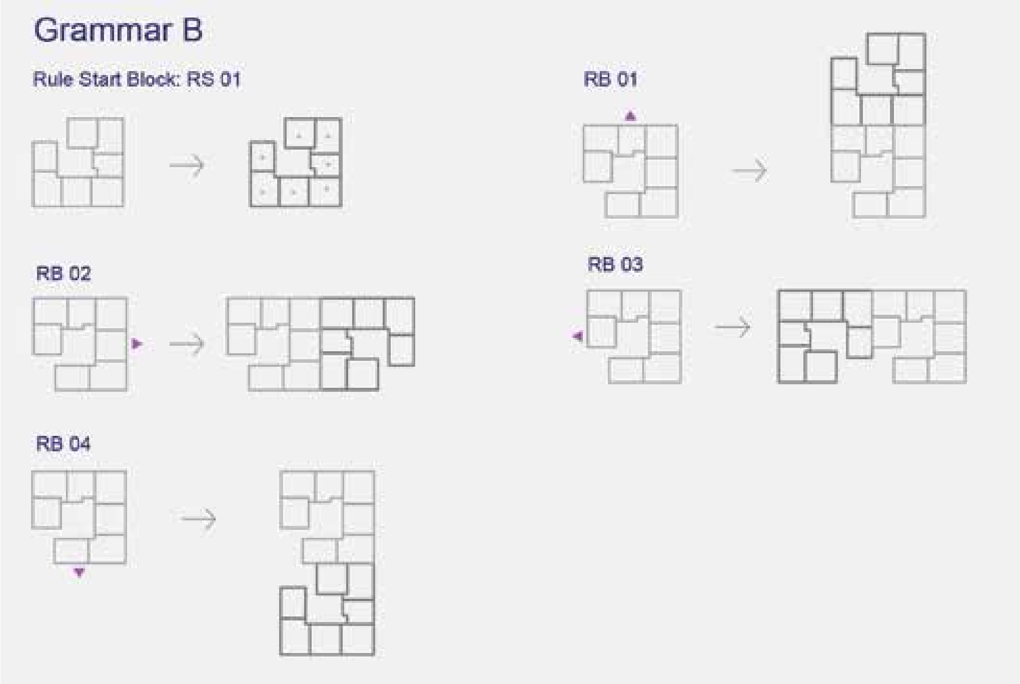


Figure 5
Derivation of a block with an empty lot.

Figure 6
Grammar B.



ability (Correa, 1999, p.109) and can transcend the set of design solutions from a few additional rules that are not part of the initial urban plan proposed by Correa. Additional rules can also be set to react to pre-existing features such as natural barriers, rivers, topography and empty spaces, among others. Although not formally expressed such rules are already present in Correa's design.

After analyzing Correa's project and developing a grammar for it an important issue has emerged: although the grammar allows the incremental growth of the housing development, how can the overall result display such an orderly character? This issue leads us the question of the design being a bottom-up or top-down process.

To achieve his concepts of incrementality, pluralism and malleability, Correa, resorts to a design system which is supposed to be implemented in a bottom-up fashion. Similarly to many natural phenomena where order emerges from a multiplication of local interactions eventually represented by a local rule, Correa's plan intensions are best captured by a bottom-up grammar where local rules provide not just the incremental procedure but also the underlying order which is always a goal in planning. This can explain the predictability of the result, despite its spontaneous characteristic. With this in mind, we could argue that, although a hypothetical top-down grammar may computationally generate the same shape and order, from the analytical viewpoint it fails to capture the conceptual principles underlying the system and therefore they cannot be considered equivalent.

Finally, a subject that needs further attention involves considering how the incremental structure of these grammars deal with the subject of neighborhood facilities location. Such theme is present in Correa's plan but rules are not formally expressed

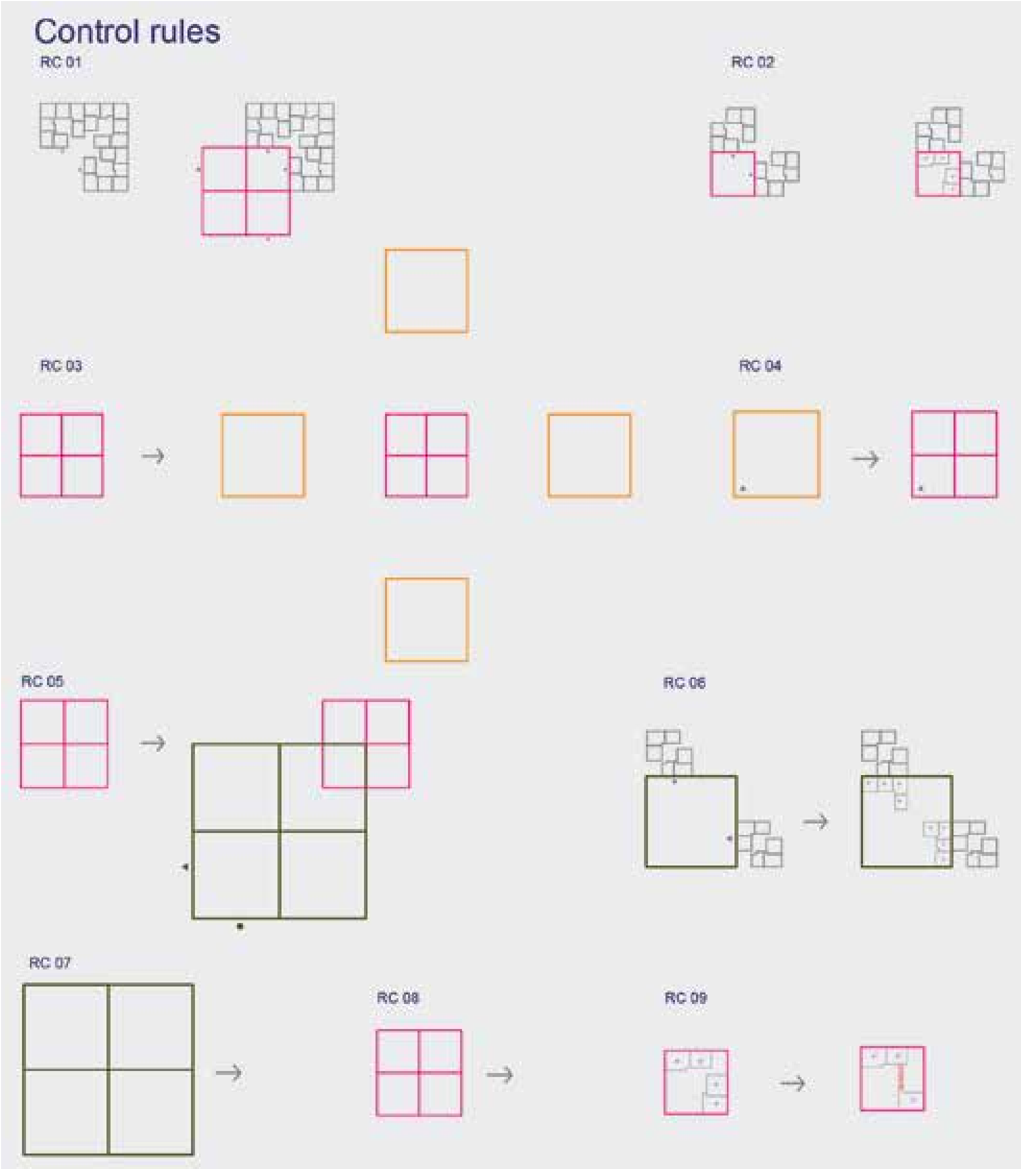


Figure 7
Control Rules.

and as a design attitude it seems that Correa simply decided their location using them as a compositional item, therefore in a top-down fashion. However, considering that one of the goals involved in

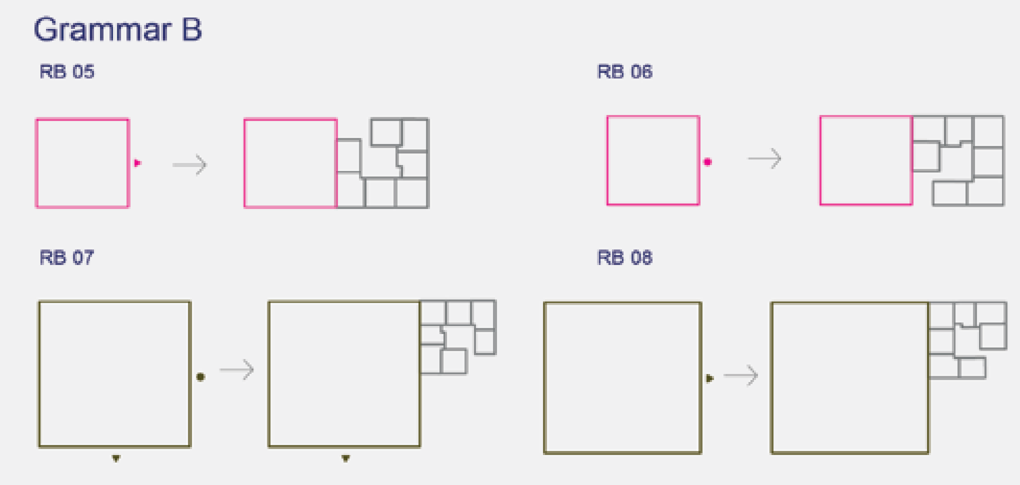


Figure 8
Rules RB 05 to RB 08.

the design is to follow an incremental growth principle, this subject needs a more careful and profound study regarding the definition of facility requirements for community planning social housing developments. This subject will be extensive enough for a future paper.

ACKNOWLEDGEMENTS

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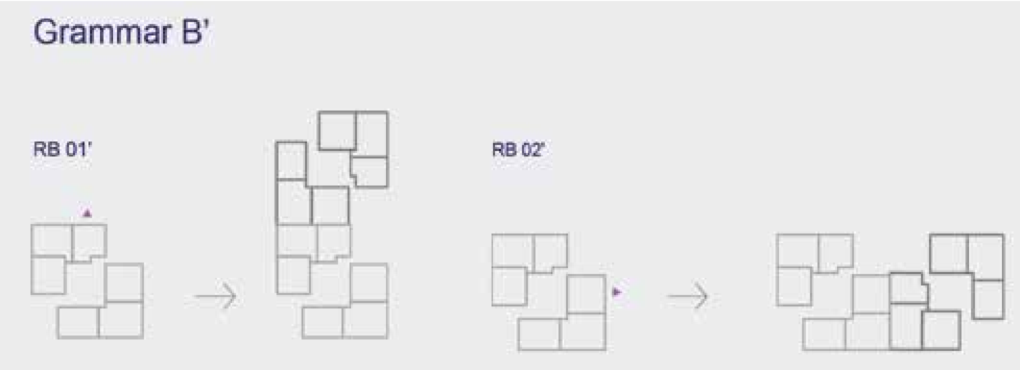

Figure 9
Grammar B'.

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The Language of Mozambican Slums

Urban integration tool for Maputo's informal settlements

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Abstract. *A shape grammar was developed for analyzing the evolution of Maputo´s slums with the strategic objective of capturing the evolution of house types and understanding the social agreements behind the spatial relations of their house elementary spaces in order to reuse such rules for the purpose of rehabilitation. This paper shows preliminary results of the research and aims at developing, based on the resulting grammars, a parametric tool able to execute morphological analyses, simulations and generate improved design solutions for the qualification of Maputo´s informal settlements.*
Keywords. *Shape grammars; urbanism; computation; regeneration; informal settlements.*

INTRODUCTION

This paper introduces a new approach for an urban simulation framework for deteriorating unplanned settlements in the city of Maputo (also known as Caniços), areas that often are regarded as 'slums'.

According to UN-Habitat's report (2003), *The Challenge of Slums*, in 2003, 31.6 per cent of the world's urban population lived in slums or squatter settlements. The 2010 report - The UN State of African Cities – states that Mozambique's urban population will raise from 9 million in 2010 to 15.6 million in 2025, confirming the country's position as having a significant growing of urban population for the next few decades.

The difference between an informal settlement, an unplanned settlement, a slum, or a deteriorated urban area is not always easy to define (despite the UN-Habitat (2006) definition). In reality all these areas often overlap in terms of their characteristics, function and appearance. Not always is an informal settlement a slum, or is a slum created in unplanned areas, but it is fair to say that in most cases slums happen to be informal or unplanned areas that are suffering from multiple physical or socio economic problems (Karimi and Parham, 2012).

RESEARCH PROJECT

This paper shows preliminary results of a PhD research aimed at developing a parametric tool able to execute morphological analyses, simulations and generation of improved design solutions for the qualification of Maputo´s informal settlements. The main goal is the creation of an integrated model that substantiates planning decisions and presents itself as a viable methodology in the search of more sustainable solutions.

This model is based on Stiny's shape grammars (1980) as means to elaborate plans capable of adapting to changes in premises without losing its urban, civic and environmental integrity. It is claimed that such a model has the ability of maintaining the urban and aesthetic coherence and the harmony with the place of intervention due to the capability of shape grammars of capturing the morphological characteristics of house types and therefore the features which are inherent to the dynamics of use, to the cultural identity and social dwelling protocols (Habraken, 2000).

The work is structured on the hypothesis that there is a grammar capable of, in a common language, capturing simultaneously the intrinsic values of the informal the needs regarding infra-structure requirements and respond in general to local population's needs. For the latter purpose, the research proposes the use of urban design quality standards to constrain the grammar within qualitatively validated boundaries.

This methodology uses the Shape Grammar formalism resorting to its analytical and generative capabilities. The analytical process enables the identification of the rules that generate informal urban fabrics, hence it permits the description through Shape Grammars of the emergent phenomenon of the informal. It also identifies representative fabric samples that reveal objective qualities which will be used to reference the valuable boundaries for grammar parameters. Secondly, the generative process will aim at the creation of a design grammar that will adapt the rules inferred in the first process to the goals defined in a development vision. It will consist in the contextualized adaptation of the rules with the strategic objective of rehabilitation and infrastructuring in order to improve the cultural setting. Also, it is intended to develop an interpretative consistent model that allows the deduction of the syntactic and semantic rules by aggregating the analysis systems - Spacematrix (Berghauser-Pont and Haupt, 2010) and Space Syntax (Hillier and Hanson, 1984) - in a substantiated operational base for decision support. It can then check the validity of the interpretative model and of the proposed digital implementation in order to promote the generation of more sustainable urban solutions within the context.

Finally, by recurring to shape grammars and using them in a bottom-up fashion one may be able to deal more easily with the emergent phenomena that typically occurs in informal settlements by adding new rules which express a local emergent recurrent pattern without losing the main order intended for the planning strategy.

CONTEXT

Authors like Paul Jenkins (2012) and Isabel Raposo and J. Oppenheimer (2008) have been revealing a weak interest by Mozambique authorities in urban development and weak capacity of the programs of decentralization by the municipality of Maputo that underestimates the tendencies of expansion of these settlements (the foresight is of 2,5 million in 2010 growing up to 4 million in 2025 in the city of Maputo). *"Why do strategic approaches to urban development generally not recognize emerging peri-urban forms as valid and work with these, rather than assuming these need to be replaced?"* (Jenkins, 2012). Even The Challenge of Slums (UN-Habitat, 2003) report *"suggests that in-situ slum upgrading is more effective than resettlement (…)"* and that as *"(…) slums are in fact the dwelling places of much of the labour force in their cities, they provide a number of important services and are interesting communities in their own right.(…)"* (UN-Habitat, 2003).

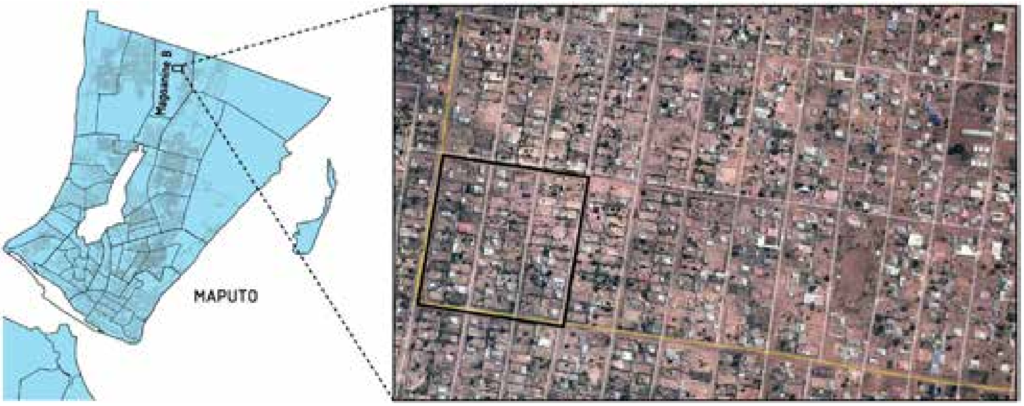
It seems then necessary to find new ways to understand the qualitative properties of existing urban solutions so that we can consistently evaluate them and propose new ones. Such processes of revitalization can be modeled and simulated through generative systems in a bottom-up approach.

THE CANIÇO SHAPE GRAMMAR

The idea of defining a Shape Grammar applied to the structure of Maputo´s slums (so called 'Cidade de Caniço') appears, first of all, like an analysis of a social space displaced from the urban process and secondly, with the strategic objective of rehabilitation.

Here we present the preliminary results of this ongoing research. The shape grammar presented here is based on the *Built Environment Study* (An-

Figure 1
'Bairro' Magoanine B in the city of Maputo. Sample of 'Unofficial Planned fabric (Google Earth).



dersen et al., 2012) data which is part of the broader research program designed by Prof. Paul Jenkins – *Home Space Maputo*. It is based on what Andersen et al. and Jenkins (2012) define as 'Type A' houses. In *Home Space Maputo – Built Environment Study* (Andersen et al., 2012) the *"many different house plans have been divided into five general house types. It is however important to stress that many of the house types overlap each other; some house types become transformed into other types (…). These five general house types are classified as the most common."* (Ibid). Accordingly to this study, the first phase of the house building construction often is to start with the most basic type. Type A house is then the most simple, with only two divisions. *"The house is entered from the center of the long façade directly into one slightly larger room and with further direct access to a bedroom. The house has one private room while the 'sala' is for receiving visitors and at times acts partly as a kitchen"* (Ibid).

The plot and the block shape and size are taken from a sample of the 'bairro' Magoanine B (Figure 1) described in Home Space (Jenkins, 2012) as an 'Unofficial planned area'. This particular area was chosen because unofficial planned areas, *"which had community / private planning and sub-division interventions at some period, but were not registered formally in the land cadastre and/or registry"* (Ibid), show a certain level of regularity in terms of urban layout that facilitate the definition of the grammar at this stage.

In order to focus on the fundamental components that constitute a typical plot, other elements are considered such as trees (which can be preexistent) and the toilets separated from the house buildings.

Designs are shown bi-dimensionally. The grammar develops by configuring the arrangement of the plots and then placing the basic form of the house (a 7m x 3.5m rectangle) in each one of them. Additionally, the rectangle is divided in two functional zones, as *"the most simple house type and in general has two divisions"* (Andersen et al., 2012) - private and social. Without any reference of construction timing or order, it´s here established that the placing of the outside toilets happens before any other extension of the house is made. The same order issue is presented with the trees, especially with the larger types. It´s assumed that most of them existed before any kind of land division. For design purposes it´s used the average treetop diameter of the three most common species to determine constraints regarding the placement of houses in relation to the tree's position.

GRAMMAR

The view of most informal settlements suggests an organic and almost chaotic land occupation. However, Paul Jenkins's (2012) studies identify four de-

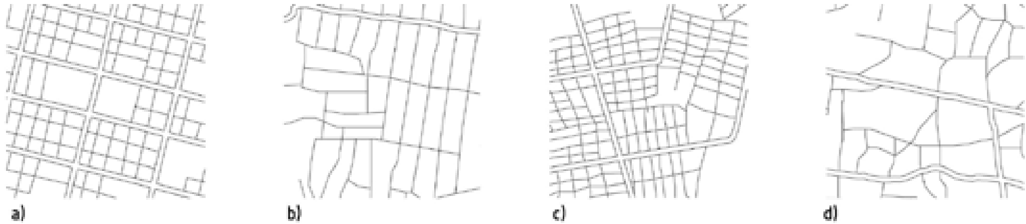


Figure 2
a) Officially planned; b) Unofficially planned; c) Upgraded; d) Un-planned (in Home Space Maputo, Jenkins 2012).

velopment statuses for land occupation in Maputo city, according to different criteria such as the level of planning, land registry and socio-economic conditions (Figure 2). Those statuses are:

"Officially planned – areas which had state planning and sub-division interventions at some period (…);

Unofficially planned – areas which had community / private planning and sub-division interventions at some period (…);

Upgraded - areas which had been unplanned but had state, community or private planning or sub-division (…)

Un-planned – areas which had no previous (…) planning or sub-division, often referred to as 'spontaneous' or 'informal' areas (…)" (Jenkins, 2012).

The research focuses on the latter three statuses – the ones that show some kind of self-organization despite of any level of state/private intervention or planning. The grammar presented here is then the first approach to the most 'regular' status of the three that reveal 'informal' qualities - the 'Unofficially planned'.

The grammar is divided in three general stages. The first one relates the plots in order to create blocks. The second stage places the Type A house inside the plot and the third configures the house extensions and other components like outside toilets and trees.

Stage 1 - Plots and blocks

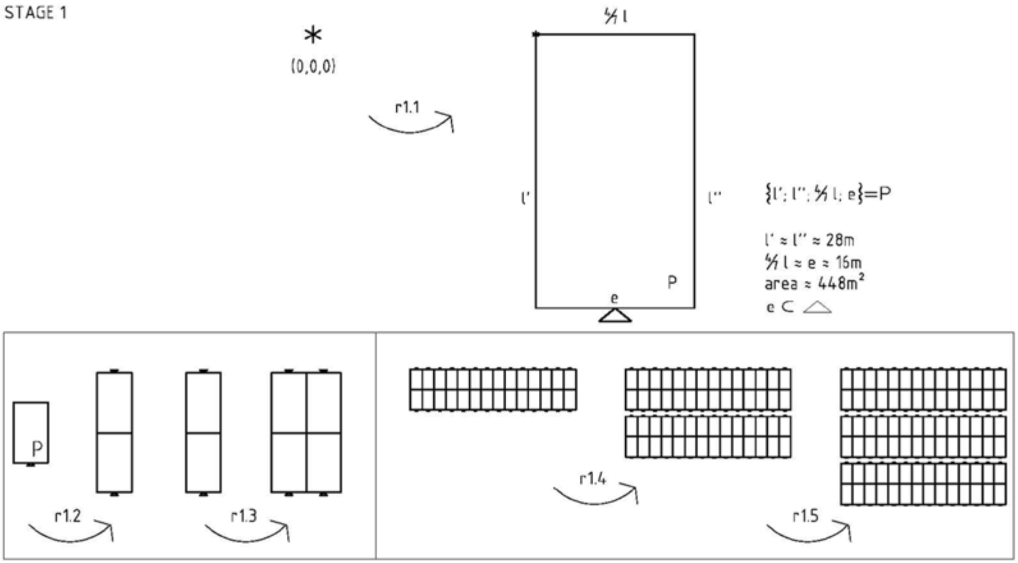
The composition starts with a given point (0,0,0) associated with the symbol * (Figure 3). To this initial shape is then established the location of the first plot. The plot is for now represented by the rectangle *P*. Rectangle *P* is 28m x 16m (average plot size from the sample shown in Figure 1) and it is composed by the lines *l'*, *l"*, *4/7 l* and *e* (which define the limits and the entrance side of the plot). Line *e* contains at its midpoint a triangle symbol for the entrance.

Once the first plot is established, other plots are added in order to create city blocks. Rule 1.2 mirrors *P* by its *4/7 l* line and Rule 1.3 copies the mirrored plots thirteen times until there is a twenty eight plots city block. From here the blocks are replicated orthogonally nine meters away from each other (the average street width). This presentation uses three city blocks (eighty four plots).

Stage 2 - House in the plot

After the city blocks generation, Type A houses are placed in each plot (Figure 4). *"Three general tendencies were recognized regarding how the houses of this type where located on the plot. The most common situation was the house located in the very far corner of the plot and with two sides of the house connected to the perimeter walls (situation 1). The next common location of the house on the plot is where the short end of the house was connected to the plot boundary and closer to the street (situation 2). Some cases also had their house centrally free standing on the plot (situation 3)"* (Andersen et al., 2012). Because this is the only quantitative information for each of the three situations, it's established the probability of occurrence for each of the situations: *situation 1* (the most common) will occur three times in every six cases; *situation 2* will occur two times in every six cases; *situation 3* will occur once in every six cases. The house is represented by the 7m x 3.5m rectangle *H*, composed by the lines *a'*, *a"*, *b'* and *b"*. Rectangle *H* can

Figure 3
Stage 1 in the grammar - Plots and blocks.



be positioned horizontally (if *a* = 7m then *b* = 3.5m) or vertically (if *a* = 3.5m then *b* = 7m) inside the plot. In no case Type A house appears in the front of the plot. One important issue raised was the probable pre-existence of trees. Trees are represented by circumference *i* and its diameter corresponds to each species average treetop diameter. To ensure that no house is placed under a tree, two conditions are established. The first is that circumference *i* cannot intersect rectangle *H* and the second is that circumference *i* cannot contain rectangle *H*.

To control the placement of rectangle *H* (or any other component) inside the plot, to each side of rectangle *H* (*a'*, *a''*, *b'* and *b''*) is added a dimension arrow *d* (*dh* for horizontal arrows and *dv* for vertical ones) that will manage the distances between each side of the house (rectangle *H*) and the limits of the plot (rectangle *P*).

Situation 1 (rule 2.1) is the most common location of the house (three in every six cases), where its corner coincides with one of the far corners of the plot. Whether the house in a vertical or in horizontal position, the condition is that *dv1* = 0 plus *dv2* = l - *b* and that *dh1* = 0 or *dh2* = 0 depending on the house being placed in the right or in the left corner of the plot.

In *Situation 2* (rule 2.2), where only the short end of the house is connected with the plot boundary (anyone but the front) there are different conditions depending on vertical or horizontal positioning. If it is horizontal then *dh1* = 0 or *dh2* = 0 depending on the house being placed in the right or in the left side of the plot. Also *dv1* ≥ 1 to ensure some space in the back of the house and *dv2* ≥ *l*/3 (since there is no case where the house is placed in the front of the plot it was established that the minimum distance to the front end is one third of the plot length – about 9.3 meters). If it's vertical then *dv1* = 0. Also *dh1* ≥ 1 or *dh2* ≥ 1 depending on the house being placed more to the right or more to the left side of the plot, ensuring some space in the back of the house in any of the cases.

In *Situation 3* (rule 2.3) the house has a centered position in the plot. None of its walls touch the boundaries of the plot which means that no distance *d* equals 0. So *dh1*, *dh2*, *dv1* ≥ 1 and *dv2* ≥ l/3,

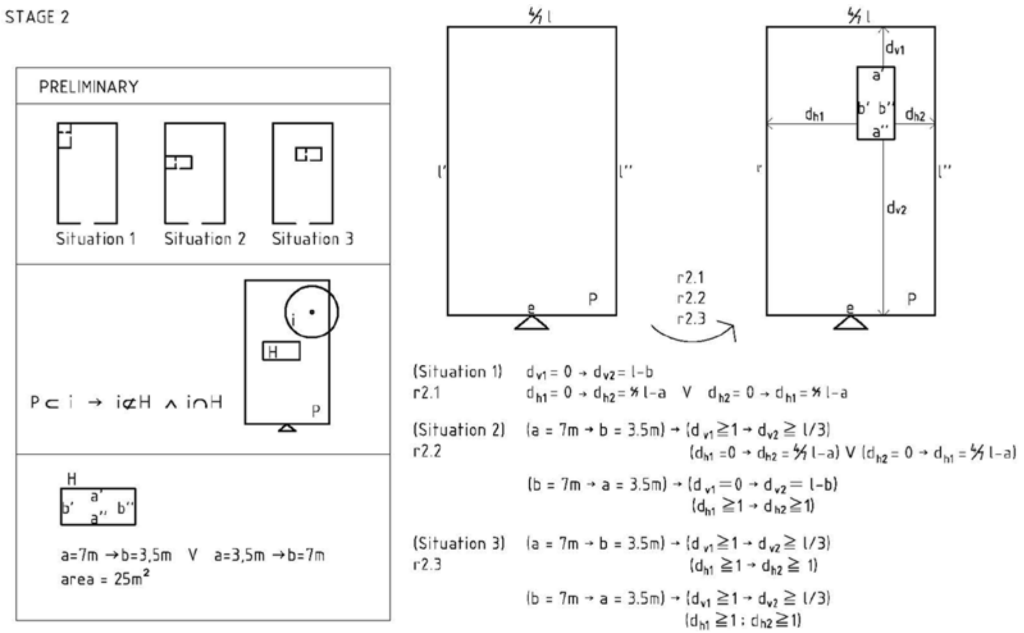


Figure 4
House location in the plot.

maintaining the same criteria of placing the house away from the front.

Stage 3 - Extensions and components

"The Home Space study provides evidence that the location of toilets and bathrooms most commonly are in a separate building or a screened off location as far as possible from the main house. This configuration was seen in 74% of the cases" (Andersen et al., 2012). It also shows that the transition from outdoor to indoor toilets corresponds to an upgrade process that seems to be slow due to the lack or insufficient sewage infrastructures. Because Type A house is the most basic one (associated with the lower income families) and corresponds to the starting stage of the house building construction, it is settled that for this type all toilets are outside of the house. For the grammar the toilets are represented by the 1.5m x 1.5m square *T*, composed by the lines *p1*, *p2*, *p3* and *p4* (Figure 5). Square *T* is inside rectangle *P* (plot). Another observation we can make is that none of the examples shown in Home Space have the toilet placed in the front end of the plot. So line *e* (from rectangle *P*) can not contain any line *p* (from square *T*). To ensure a considerable distance from the house, it is established that the toilet must be placed in one of the other three plot's limits and that the minimum distance to the house is six meters. This minimum distance is assured by the placement of an auxiliary circumference *c* with a six meter radius. Circumference *c* is centered with square *T*. Circumference *c* cannot intersect or contain rectangle *H* (house).

The next stage is to divide the house (rectangle *H*) in two labeled divisions – bedroom *B* (*B* = 3m x 3.5m = 10.5m2) and 'sala' *L* (*L* = 4m x 3.5m = 14m2) – and mark the door label with a triangle. As mentioned above, the main entrance is in the center of the long façade. Because there are two, the door label is to be placed in the one that has a longer distance *d* (whether it is a *dv* or a *dh*). This condition denies any chance of having a door facing directly at the boundary wall. It´s important to stress that the

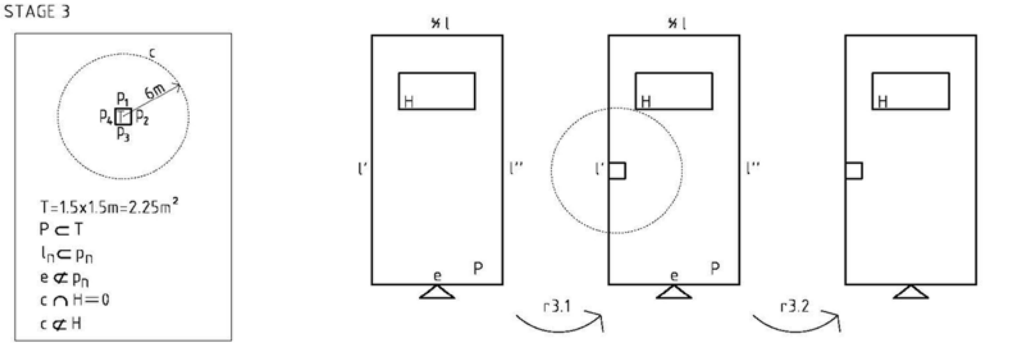


Figure 5
Toilets location; House division.

yard is a scene for *"everyday life and a space for socialising, household work and sometimes also a space for economic activities"* (Ibid). The toilet door follows similar criteria. In this case the only condition is that it never faces the front side of the plot (line *e*). In other words, it can only be placed in its horizontal distance *dhn* or in its vertical *dv1*.

"House type A can be extended in various ways" (Ibid). The extensions used for the grammar follow the four examples shown in Home Space. Type A houses are extended with additional one or two rooms with similar size and shape as the existing ones (larger extensions would transform the Type A house into other types). Therefore, five different layouts are created for Type A house: *extension 0*, *1*, *2*, *3* and *4* (in *extension 0* the house keeps its original configuration - Figure 6). In the absence of quantitative information, it is established that all the five layouts are applied in the same number (each is applied once in every five cases). The application of these transformation rules implies the elimination of the labels in the house and the insertion of the doors.

Extension 1 adds one room to the front of the house. *Extension 2* creates a big living area in the front of the house and a new entrance way to the side of the 'sala' (formally labeled with *L*). The only condition here is that the distance *d* at this side must be greater than the opposite *d*. This will grant a larger yard area in front of the new entrance of the house. The only extension that can be made to the back of the house is *Extension 3*. It basically mirrors the house to the back or to the front, creating a new inner door. If the extension is to the back, the distance *d* in the back of the house has to be bigger than 4.5 meters (3.5m for the new body plus 1m for the new back door passage). *Extension 4* creates a large living room to the front plus a 'veranda'. *"The veranda is not only a transition space between outside and inside - which can be used for practical purposes as cooking, storage, or a social space for - but also a way of representing the house in the neighbourhood. Many of the verandas had burglar bars and some of these were richly ornamented"* (Andersen et al., 2012). This extension requires that the house have a horizontal position because the *"veranda is always facing*

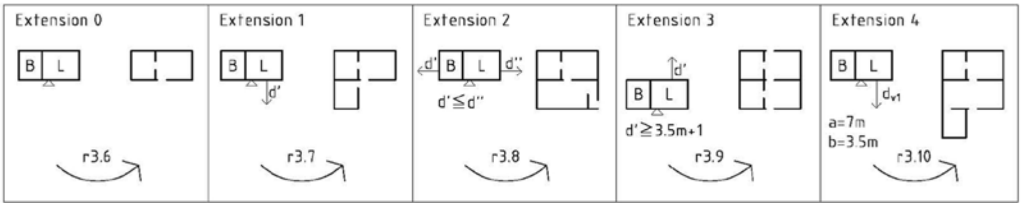


Figure 6
House extensions.

Figure 7
3D Model.

the street" (Ibid).

"Trees provide shade and hence create spaces for socializing and domestic work, bear fruit or can figure as decorative elements. Trees also had a spiritual function vis-à-vis the reverence for ancestors and traditional ceremonies often involve trees. The 'quintal' is a space for social interaction where e.g. visitors can be received in the shade under a tree. The majority of the cases, 73%, have a shade providing tree in their yard and in 2/3 of these cases, the tree is a big mango tree and in other cases there are mafureira (Natal Mahogany) or canhueira (Marula) trees, both producing fruits" (Andersen et al., 2012). As seen above there is a preliminary condition about the possible pre-existance of trees. In order to control the placement of planted trees, there is one first rule that defines the contour of the house. This contour line prevents that the tree is placed over the house. Thus the contour line cannot intersect circumference *i*.

Despite the fact that Type A houses only have one floor and for that the grammar is essentially bidimensional, there are a set of rules that extrude the print for visualization purposes. This third dimension uses basic façade composition shown in Home Space as well as the low pitched roofs (made of corrugated iron sheets). When applied to the eighty four plots, the 3D visualization gives us a better view of the set as it represents a powerful and effective way of communication (Figure 7).

CONCLUSION

The research described in this paper constitutes the first step towards the development of a computational model for Maputo informal settlements. The ultimate goal is to use this model to support decision in urban interventions that have similar spatial features and to improve them from the environmental viewpoint by manipulating the rules in the model. The model uses shape grammars to encode the underlying syntactic rules describing the language of the 'Caniços' which capture the social features underlying these morphological types. It aggregates two essential grammars: the grammar to generate the urban fabric and the grammar to generate the houses and its components. This paper describes the preliminary results of the second generative grammar.

An important point for discussion here is to evaluate the capacity of the grammar of really capturing what are the reasons behind the transformation happening in the 'Caniços'. In many situations, different grammars can be used to produce the same formal arrangements, in other words, in some circumstances different sets of rules are able to produce the same shapes. However, as analytical tools there is only one grammar which is capable of reproducing simultaneously shape and the generative process which originated the shapes of a corpus of designs used as case studies. Therefore, if a grammar produces the shape of our case studies in Maputo, this is not enough evidence that the grammar is efficient for our purposes. We still need to validate the grammar against evidence of the real motivations behind one or another particular transformation to check if it is really replicating the social behavior underlying such transformations. This is important considering that the reuse of the grammar is the main goal in mind and that it is supposed to deal with the typical social behavior while providing some degree of control to improve the final outcome. This validation still needs to be done and is planned as the next step of the research.

According to Andersen et al. (2012), *"buildings are in continued process, always under construction and in various stages of being extended, appended, built or finished. This process sometimes spans over decades (…)"*. It has to be stressed that this grammar deals only with what could be considered as the most basic module unit of house buildings in peri-urban Maputo though it encompasses some evolutions of the Type A (one of the cases may be included in Type B) houses. As Home Space Built Environment Study (Andersen et al., 2012) mentions, *"the size of the house was clearly linked to wealth of the residing household"* though *"the survey does not carry any clear evidence of a relation between economic status, location in the city or planning category"*. This means that Type A house evolution is in most cases linked with socio-economic changes in the household which need further understanding.

Evidence raised here was the low density occupation of the plots underlining the clear importance of the yard as a space for social interaction, domestic work or for small economic activities. Another aspect is that this low density occupation is responsible for an increasingly spreading urban sprawl effect which creates a great dependency on car use in a city with no adequate traffic infrastructure and a large amount of population with no motorized means of transport. Therefore, the study of densification strategies within the existing structures will be a key issue in terms of the development of planning strategies. Densification studies still need to be developed having in mind three kinds of extension opportunities: (1) plot subdivision; (2) house extension and (3) addition of areas for commercial activities. Evidence of possible valid occupations may be captured from the analyses of denser and more compact areas.

Another key issue will be the transformation of the grammar in terms of sanitation conditions. According to Andersen et al. (2012), one of the main aspirations of these populations concern improving water and sanitation facilities, such as having running water on the site, including building a bathroom inside the house. This is an essential aspect to be developed in order to improve the living conditions.

The current grammar is essentially a bi-dimensional one due the fact that the case studies worked until now refer to ground floor houses, but if a densification strategy is to be taken in consideration, evidence from other informal areas where density is already higher and construction includes taller informal buildings will need to be incorporated in a more complex grammar. This work is already under development. The only 3D approach done until now consists of a simple extrusion of the layouts generated by the grammar (Fig.2) which is used for visualization purposes.

Finally, one of the main problems involved in slams' sprawl is the fact that it generates continuously spreading homogeneous areas where no urban hierarchies are usually found. A bottom-up grammar will tend to simply replicate this behavior. Therefore, in planning terms it becomes evident the need for introducing evaluation and control mechanisms (and an additional grammar) which should react to the changes in the occupation conditions (and density) and generate the additional features that otherwise would not be defined by the grammar. This process will be the subject of a future paper.

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Gulou Structure Grammar and its Computer Implementation

A computational approach to preserve the ethnic building technique and to guide new designs

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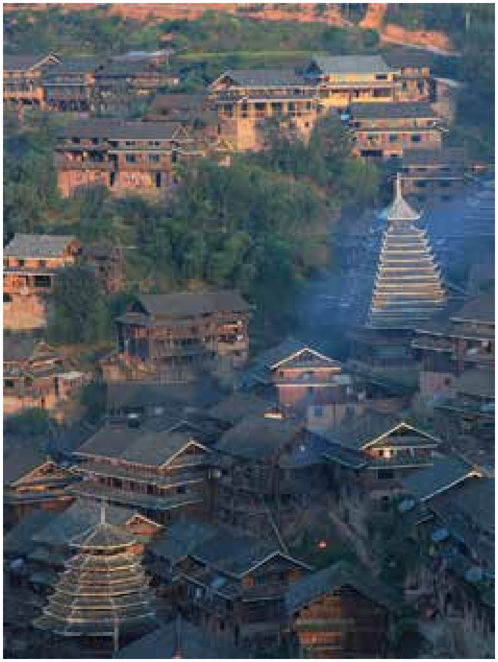
Abstract. *Gulou is a type of building found in ethnic Dong people's settlements in south west China. It plays a significant role in the traditional Dong architecture and shows both social and technical values. In the near future the technique as an intangible culture heritage would face the risk of extinction because of globalization. The paper argues that the use of formal grammar and computer tools could help the preservation and learning of the design knowledge of Gulou Structure and develop Gulou designs which would be adapted to modern needs. A shape grammar called Gulou Structure Grammar (GSG) and its computer implementation are made to achieve the goals of capturing the design knowledge of Gulou structure, generating new Gulou designs and promoting the education of Gulou building techniques.*
Keywords. *Gulou structure; shape grammar; parametric model; ethnic building technique.*

INTRODUCTION

Gulou is a type of building found in ethnic Dong people's settlements in south west China. Dong settlement is composed of the basic family group "Dou", every Dou should have its own Gulou as a symbol for the family group. There trend to be 2 to 4 Gulou in a village (Figure 1). Gulou plays a significant role in the traditional Dong architecture and shows both social and technical values. The wooden tower is the most important public building in a settlement as the village council and the senior statesmen's centre. It also acts as an important place for social activities and communications. For example, the children should be given their names in Gulou; people gather in the Gulou after work to exchange ideas and chat with each other. All the cultural and social activities of Dong people are related to and influenced by Gulou. The culture identity and value system of Dong people are emerged from the activities carried out in Gulou.

Apart from the social importance and value, Gulou is also famous for the unique uprising shape and the excellent building techniques without using any



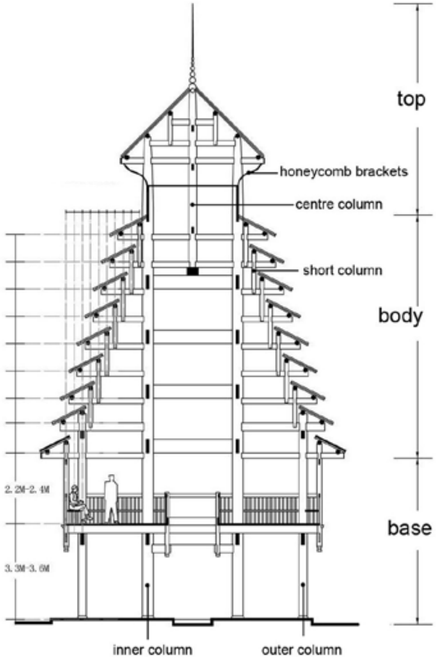


Figure 1
Two Gulou in a Dong village.

Figure 2
The typical section of Gulou.

metal parts. As an ancient high-rise wooden structure which is still been applied nowadays, Gulou is one of the most excellent traditional Chinese wooden buildings. There are 2 kinds of main columns in Gulou: the inner columns and the outer columns. The inner columns together with the connecting beams play the very similar structure role as the core in the modern high-rise tower. The outer columns are connected to the core by beams which support the multi-level uprising structure. The flexible joint design also enhances the anti-earthquake performance. In terms of ecology, the Gulou technique accumulates the long term low-tech experience of Dong people to avoid the impact of the hot and humid weather condition. For instance, the multi-level roofs could promote ventilation while keep the interior dry from the rains (Figure 2).

Like the other developing regions in China, the old and vernacular building and technique are challenged with globalization. Seldom young men are willing to learn the technique from the old. In the near future the technique as an intangible culture heritage would face the risk of extinction. Unlike the building and construction manuals for the official Chinese traditional buildings, the rules of Gulou are not originally organized in any written form or drawing. Instead, they are passed down from generations to generations by pithy formulas. While designing and building a Gulou, the craftsman seldom produces any drawing as well. The implicit way of design makes the technique to be difficult to understand and to learn, which also limits the wide spread of the building culture. Although various studies managed to uncover the rules of Gulou building technique, few efforts were made in the area of the formal and computational approach (Cai, 2004).

The paper argues that the use of formal grammar and computer tools could help the preservation and learning of the design knowledge of Gulou Structure and develop Gulou designs which would be adapted to modern needs. Shape Grammars were successfully applied in the research of traditional Chinese wooden structures (Li, 2001) and dwellings (Chiou and Ramesh, 1995). In this paper a shape grammar called Gulou Structure Grammar (GSG) and its computer implementation are made to achieve the following aims.

1. Capture the design and construction knowledge of Gulou structure via shape grammar.
2. New Gulou design could be generated with the use of digital tools which are developed based on GSG.
3. GSG and the digital tools could be used in education to facilitate the teaching of the rules of Gulou.
4. The digital tools could be used to explore the performance of Gulou.

THE GENERATION OF GULOU STRUCTURE GRAMMAR

The authors managed to extract the compositional rules of the Gulou wooden structure. The rules were further translated to a shape grammar – Gulou Structure Grammar (GSG).

Analysis of the compositional rules of the Gulou wooden structure

The exterior appearance and interior space of traditional Chinese wooden building are entirely defined by the main wooden structure. The composition of the wooden frame is best demonstrated in sections. The function and plan design of Gulou trend to be simple due to its symbolic meaning in the village. The plan shape is usually a square, a hexagon or an octagon. Therefore the section design plays the most significant and complicated roles in the design of Gulou. During the design process, the master craftsman is in charge of the section drawings rather than plan drawings. The plan provides the guide planes which the sections will be attached on.

Gulou could be classified by the number of main columns which touch the ground. There are 2 types of main columns: Inner column and Outer column. The inner column can be composed of a single column or multiple columns. Besides the single inner column case, both the number of inner column and outer column should be even number. The research focuses on the most common type of Gulou – the 4 inner columns and 8 outer columns Gulou.

The inner columns are placed at the corners of a square while the outer columns are placed at the corners of an octagon. The relationship between the square and the octagon varies into 2 situations. In the first situation the diagonal lines of the 2 shapes are parallel while the second situation the edges of the 2 shapes are parallel. Different alignment leads to different placement of sections. In the first situation the sections are placed between the corners of 2 shapes and between the corners of the octagon and the edges of the square. In the second situation the sections are only placed between the corners of the 2 shapes (Figure 7).

The section of Gulou can be divided vertically into 3 parts: the base, the body and the top (Figure 2). The structure of the base is composed of the main columns and is rather simple. The body contributes most for the symbolic appearance of the building. It is the most important part and highly reflects the building technique of Dong people. The decorative top with fine structure acts as a balanced visual ending to the building. The following article focuses on the composition of the body and the top.

The wooden frame of the body is composed of inner column, outer column, short column, centre column, rafter and beam. The inner column and outer column are connected with beams which are cantilevered to support the eaves and rafters. A short columns are added to a beam to support its upper level beam and rafter. After several iterations the body grows to its full height and the top columns are connected to a central column by beams. The span of beams decreases level by level therefore each level gets smaller and smaller to form the taper outlook of the tower. When the decreasing reaches to the point when the position of short column will be placed on the inner side of the inner column, a centre column must be added to the section to support the upper level beams (Figure 3). Via the control

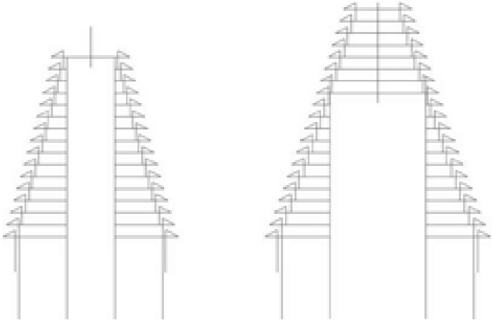


Figure 3
When the decreasing reaches to the point that the position of short column will be placed on the inner side of the inner column, a centre column must be added to the section to support the upper level beams.

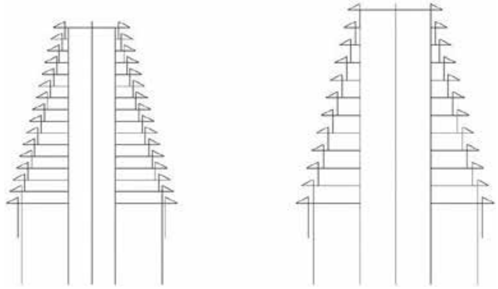


Figure 4
By the control of the position of main columns, the number of levels and the height of levels, the facade profile could be adjusted.

of the position of main columns, number of levels, height of levels and the decreasing distance of each level, the facade profile could be adjusted (Figure 4). Equalized decreasing will result in the tilted linear profile while the uneven decreasing will result in curved profile (Figure 5).

The top of the Gulou is also called "honey comb" by the extinguished look (Wu Lin, 2009). It is composed of many layers of overhanging and self-supporting wood pieces. Each layer is subdivided into many segments so the overall structure of the top is a complicated cell-looking system. The composition of the top could be illustrated by the following steps (Table 1):

1. Define the plan profile of the base of the top. In this case the profile is an octagon.
2. Offset the profile to get the shape of each level. In this case the top is composed of 6 level brackets.
3. Equally divide each edge of the profile in to N segments and get the division points. In this case N=10.
4. Connect the points with the odd number index *i* on the odd number level to the points with according index on the upper level; connect the points with even number index *i* on the even number level to the points with according index on the upper level. For instance, point 3 on the 1st level will be connected to point3 on the 2nd level; point 6 on the 4th level will be connected to point 6 on the 5th level.
5. Connect the points with the odd number index *i* on the odd number level to the points with index *i + 1* on the upper level; connect the points with even number index *i* on the even number level to the points with index *i + 1* on the upper

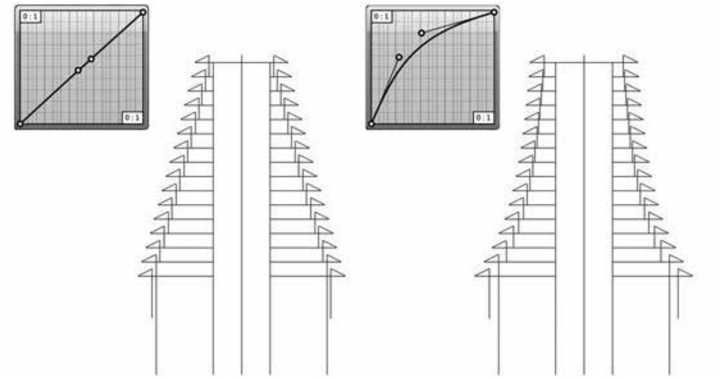
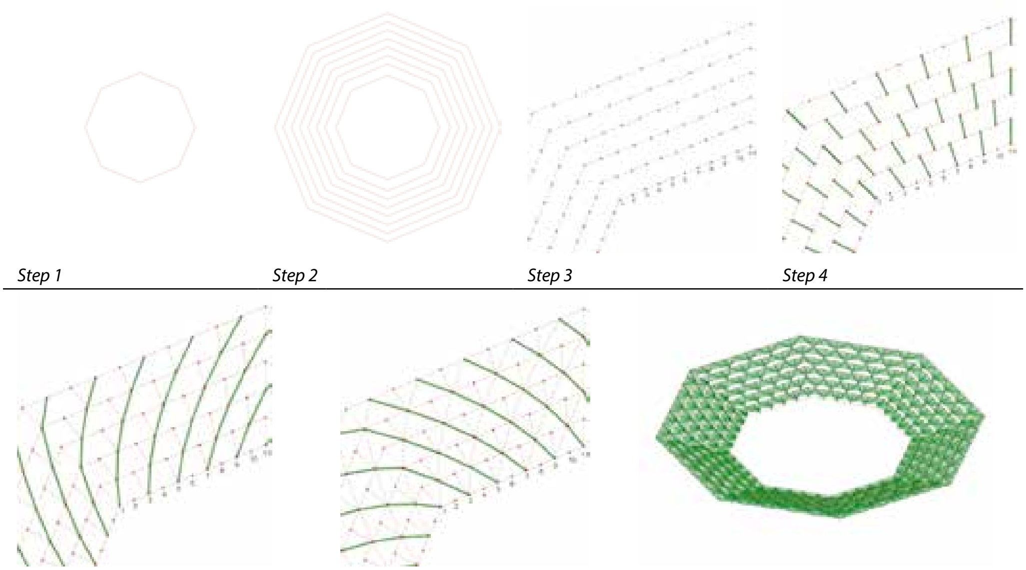


Figure 5
By the control of the decreasing distance of each level, the facade profile could be adjusted. Equalized decreasing will result in the tilted linear profile while the uneven decreasing will result in curved profile.
In this case the decreasing is controlled by a Bezier curve.

Table 1
The steps to generate the honeycomb top.



level. For instance, point 3 on the 1st level will be connected to point 4 on the 2nd level; point 6 on the 4th level will be connected to point 7 on the 5th level.

6. Connect the points with the odd number index *i* on the odd number level to the points with index *i - 1* on the upper level; connect the points with even number index *i* on the even number level to the points with index *i - 1* on the upper level. For instance, point 3 on the 1st level will be connected to point 2 on the 2nd level; point 6 on the 4th level will be connected to point 5 on the 5th level.
7. All the guide lines for the leaf-shaped brackets are generated from step 4 to 6. The brackets are attached according to the guide lines to form the base part of the honeycomb top.

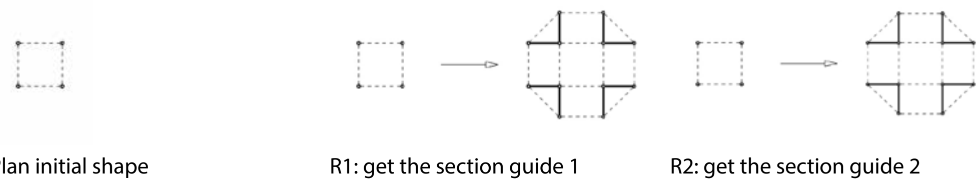
The content of GSG

After the analysis of the compositional rules of Gulou, GSG was formulated. It consists of 3 initial design and 24 rules. Rules were divided into 3 groups: plan rules (Table 2), body section rules (Table 3) and top rules (Table 4).

THE COMPUTER IMPLEMENTATION OF GSG

A parametric model was built based on GSG. Sev-

Table 2
Rules of plan generation.



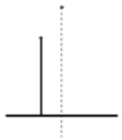
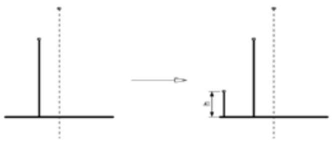
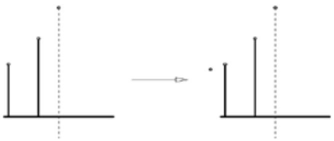
 initial shape: the inner column	 R3: get the outer column	 R4: get an end point of beam
 R5: add an outer beam	 R6: get the centre column	 R7: get an inner beam
 R8: get a rafter	 R9: get a short column	 R10: get an overhang short column
 R11: get a rafter	 R12: extend a column to a rafter	 R13: get a connecting beam
 R14: get a connecting beam	 R15: get an inner column which seats on a beam.	

Table 3
Rules of section generation.

eral key parameters were identified: type of plan, distance between inner columns, distance between inner and outer columns, height of the base, body level height, number of body level, a Bezier curve to control the span decreasing of each body level, top level height, number of top level and the increase span of each top level. Detailed parameters were also defined: cantilevered distance of beams, rafter angle, and column lower extension length. Dimension parameters were added to determine the size of the components such as the radius of columns and the height of the beams. Grasshopper in Rhino3d is chosen as the platform to develop the parametric model. Both the axis and the solid model of the wooden frame pieces can be obtained from the model (Figure 6).

THE APPLICATION OF GSG AND THE PARAMETRIC MODEL

As an ancient building type oriented from the Ming dynasty (1368–1644), Gulou is still being built and is playing an important role in the life of Dong people nowadays. It is also widely used in public parks and tourism sites in non-Dong areas for its distinguished

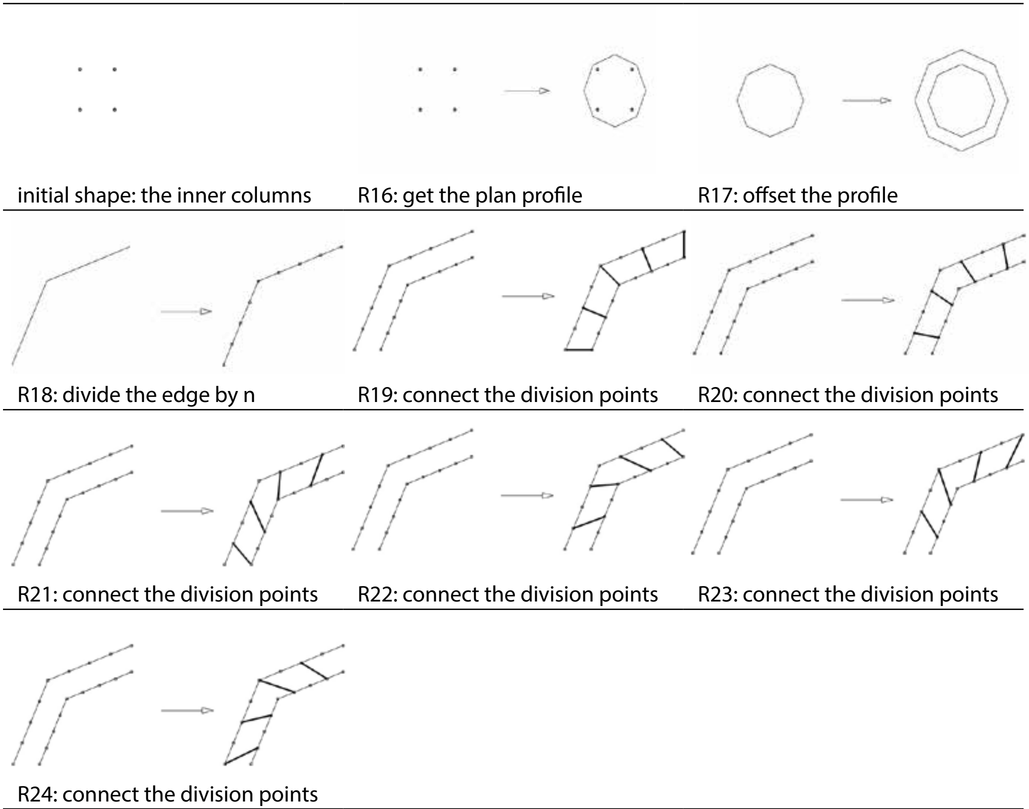


Table 4
Rules of bracket axis generation.

symbolic form and strong landmark effect. From the modern use of Gulou, it could be identified as a type of contemporary architecture. However, both its design and construction are still based on the old manual approaches. Digital technologies could serve the design and construction of Gulou as new instrument, therefore Gulou could evolve and be adapted to the information age.

The parametric Gulou model was used in the design of a landmark structure in a resort area in Sanjiang, Guangxi province. The famous Dong craftsman Wu Shikang was invited as a design consultant for the project. During the design process, a series of design models were generated with the help of the parametric tool (Figure 7). Wu gave a positive review of the tool. He held the view that the tool could rapidly generate designs according to the rules and parameters, therefore the communication with client could be carried out efficiently. Also the model provided all the dimensions of the main structure pieces and a spread sheet of the use of material. The work used to take months to do could be compressed to be finished in days.

GSG is also used in the teaching of the course: *Guangxi ethical buildings* in the architecture school of Guangxi University. Gulou is an important topic of the course. GSG and the parametirc model are introduced to unveil the design rules and construction process of Gulou. The students can learn the rules from GSG in a graphic and formal way. Then design

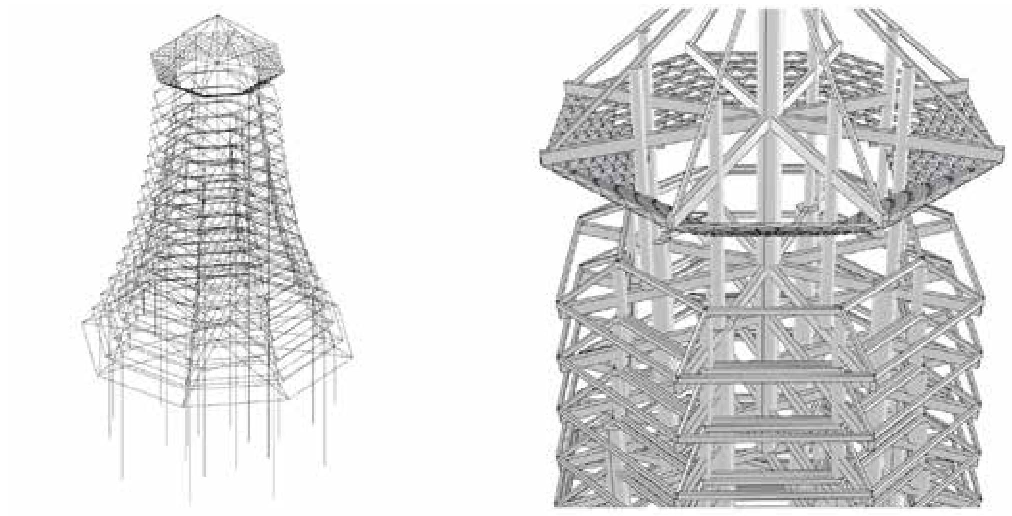


Figure 6
Both the axis and the solid model of the wooden frame pieces can be obtained from the parametric model.

experiments could be carried out. Students use their own set of parmeters to generate designs with the parametric model. The vivid digital way of teaching encourges the students to ananlysis traditional chinese buildings in a computational point of view, and to explore new designs based on the traditional building tecniques.

DISCUSSION AND FUTURE WORK

The shape grammar of Gulou structure was formulated as shown by the paper and a computer tool was made to assist the design and education of the ethnic building. However, the potential of GSG and its computer implementation is not fully explored. The paper serves as a start point for the long term

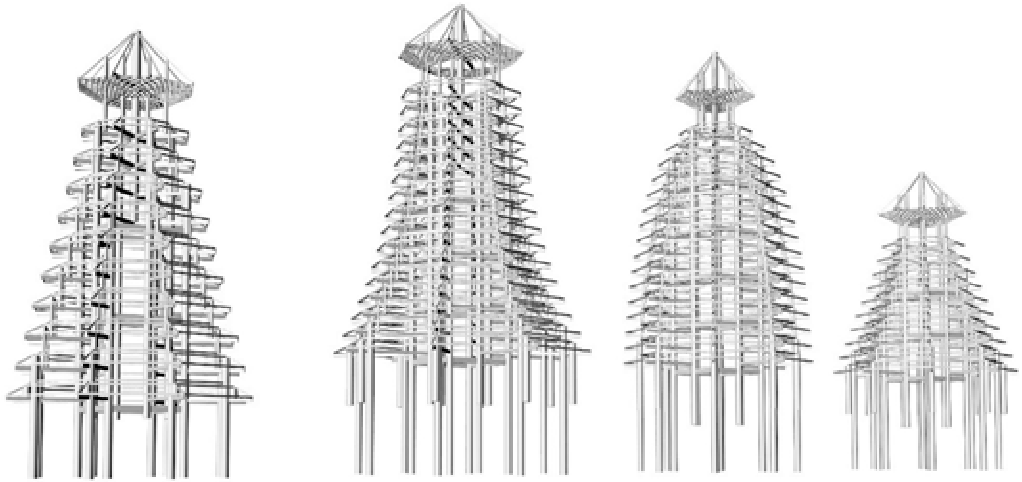


Figure 7
4 different designs are generated for the project in a tourist site.

study of the building techniques of Gulou. The future work based on GSG would address the issue of building performance evaluation, the detail wooden structure of Gulou and its implication to contemporary architecture.

The building performance of Gulou mainly contains 2 aspects: the structural performance and the passive solar comfort. The performance evaluation of Gulou should take the considerations of the culture and activities of Dong people. In this paper the structural performance is focused on material consumption. The material for building Gulou is fir. On one hand, Dong people are willing to travel hundreds of kilometers to find the right and divine fir and transport it back via man labor. On the other hand, nowadays the forest resources in China are getting more and more precious. The two factors require the size, length and numbers of the fir for Gulou construction to be carefully calculated in order to minimize the material usages while achieving the design purposes. Future work will study the relationship between the form and the structural performance of Gulou.

Passive solar comfort evaluation consists of the assessment of daylight factor, solar radiation and ventilation. They are related to the overall dimensions of the tower and the openings. There is one unique factor of thermal comfort in Gulou: there is always a fire place in the centre of the ground floor. It is a symbol of energy in Dong culture. The fire place plays the role of a heat source and will affect the air flow in the chimney-shape of the inner space. Multi-level roofs could encourage the use of daylight and natural ventilation while keep the interior dry away from the rains. Advanced performance simulation software would be introduced in future studies to unveil the ecological means in Gulou building techniques.

The detail joint design plays a significant role in the wooden structure. The sophisticated tenon-and-mortise work connects all the wooden pieces together without using any nail or metal part. The design grammar of the detail wooden structure will be carried out in the further study.

The aesthetic, structural, ecological and detailed design features of Gulou would have great implication to the design of contemporary architecture. The features could be further explored and applied to new designs. Further design experiments and practices will be carried out with the considerations of the features of Gulou. We believe that the computational design approach will help us adopt and apply the characters of ethnic building for the emergence of the new architecture.

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Computation and Performance

Volume 2

This is the second volume of the conference proceedings of the 31st eCAADe conference, held from 18–20 September 2013 at the Faculty of Architecture, Delft University of Technology, Delft, The Netherlands.

The theme of this conference is the role of computation in the consideration of performance in planning and design.
Since long, a building no longer simply serves to shelter human activity from the natural environment. It must not just defy natural forces, carry its own weight, its occupants and their possessions, it should also functionally facilitate its occupants' activities, be esthetically pleasing, be economical in building and maintenance costs, provide temperature, humidity, lighting and acoustical comfort, be sustainable with respect to material, energy and other resources, and so forth. Considering all these performance aspects in building design is far from straightforward and their integration into the design process further increases complexity, interdisciplinarity and the need for computational support.
One of the roles of computation in planning and design is the measurement and prediction of the performances of buildings and cities, where performance denotes the ability of this built environment to meet various technical and non-technical requirements (physical as well as psychological) placed upon them by owners, users and society at large.

eCAADe — the association for Education and research in Computer Aided Architectural Design in Europe – is a non-profit making association of institutions and individuals with a common interest in promoting good practice and sharing information in relation to the use of computers in research and education in architecture and related professions. eCAADe was founded in 1983.

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